AD-A047 251 SRI INTERNATIONAL MENLO PARK CALIF F/G 1/3
PILOTED FLIGHT SIMULATOR STUDY OF LOW-LEVEL WIND SHEAR, PHASE 2--ETC(U)
MAR 77 W B GARTNER, D W ELLIS, W H FOY DOT-FA75WA-3650
UNCLASSIFIED FAA-RD-77-157 NL

1 OF 2
AD
A047251

Report No. FAA-RD-77-157

12

PILOTED FLIGHT SIMULATION STUDY OF LOW-LEVEL WIND SHEAR, PHASE 2

ALL-WEATHER LANDING SYSTEMS, ENGINEERING SERVICES SUPPORT PROJECT, TASK 2

W. B. Gartner, D. W. Ellis, W. H. Foy, M. G. Keenan,
A. C. McTee, W. O. Nice

SRI INTERNATIONAL, MENLO PARK, CALIFORNIA 94025

March 1977

Interim Report

Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

NOTICE

Technical Report Documentation Page

1. Report No. 18 19 FAA-RD-77-157	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle 6 PILOTED FLIGHT SIMULATOR STUDY OF LOW-LEVEL WIND SHEAR, PHASE 2.		11 5. Report Date Mar[redacted]77
		6. Performing Organization Code
7. Author(s) 10 W. B. Gartner, D. W. Ellis, W. H. Foy, M. G. Keenan, A. C. McTee, W. O. Nice		8. Performing Organization Report No. SRI Project 4364
9. Performing Organization Name and Address SRI International 333 Ravenswood Avenue Menlo Park, CA 94025 12 181p.		10. Work Unit No. (TRAIS) 15
		11. Contract or Grant No. new DOT-FA75WA-3650
12. Sponsoring Agency Name and Address U. S. Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington, D.C. 20590		9 13. Type of Report and Period Covered Interim Rep[redacted]t. Aug[redacted]76 - Mar[redacted]77
		14. Sponsoring Agency Code FAA/ARD-743

15. Supplementary Notes

Prepared on ALL-WEATHER LANDING SYSTEMS, Engineering Services Support, Project 4364, Task 2

16. Abstract

Task 2 of the All-Weather Landing Systems project is concerned with piloted flight simulation tests of various techniques designed to aid the pilot to detect and cope with low-level wind shear on approach and landing. This report documents the tests of Phase 2, a comparative evaluation of the most promising panel-displayed techniques from the Phase 1 study.

The operational situation of a DC-[illegible] aircraft landing in Category I visibility with ILS guidance was simu[illegible]. Winds corresponding to inversion-layer, frontal, thunderstorm and "no-shear" conditions were simulated to provide test profiles. The "baseline" aiding concept was the conventional DC-10 manual approach management. The aiding concepts tested were based on ground speed displays (first experiment), flight path angle (second), and modified (acceleration-augmented) flight director (third experiment).

The results showed that ground speed displayed on the airspeed indicator and the modified flight director can improve performance significantly over baseline, especially on the thunderstorm wind profiles, which was the most difficult condition.

This work was accomplished by the AWLS team (SRI, Bunker Ramo Corporation, and Collins Avionics of Rockwell) with Douglas Aircraft Company as simulation subcontractor.

17. Key Words	18. Distribution Statement
wind shear DC-10 flight simulation ground speed flight director airborne instrumentation acceleration-augmented	Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia, 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	180	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

410 281 4B

METRIC CONVERSION FACTORS

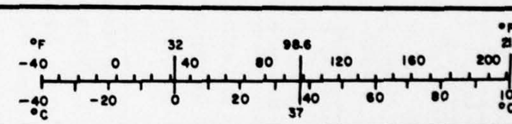
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

The purpose of Task 2 of the All-Weather Landing Systems (AWLS) project is to develop and implement a manned flight simulation program to (1) investigate terminal flight operations, emphasizing wind shear effects, and (2) determine the operational and technical role of head-up displays. This interim report describes the results obtained by the AWLS team--SRI, Bunker Ramo Corp., and Collins Radio Group of Rockwell-International--on Phase 2 of a series of manned-flight simulation experiments on the capabilities of various head-down aiding concepts to assist the pilot in coping with low-level wind shear. The sponsoring organizations are FAA Wind Shear Program Office and ARD-740; the Technical Monitor is W. J. Cox.

TABLE OF CONTENTS

Preceding Page Blan

CONTENTS (Concluded)

ILLUSTRATIONS

TABLES

I INTRODUCTION*

A. Program, Objectives, and Approach

Wind shear may be described as a change in wind speed or direction occurring over a relatively small spatial change; an example is a change from 20 knots of headwind at an altitude of 300 feet to 10 knots of headwind at 150 feet. When such wind variations occur at low altitudes during aircraft approach and landing or during takeoff and climbout, the attendant changes in the aerodynamic forces can lead to a hazardous situation. The FAA Wind Shear Program Office is conducting investigations and system developments with the goals of giving the pilot a warning of potential wind shear hazard and aiding him in coping with the variable winds if he inadvertently encounters a hazardous wind shear condition. There is no intent to develop methods or teach pilots to fly intentionally through hazardous conditions.

The manned-flight simulation study reported here is one of the wind shear investigations, and is concerned with the evaluation of certain well defined airborne aids. The first study in the series, Phase 1, involved manned simulation tests and was designed as a comprehensive survey of pilot-aiding concepts that would include near-term, readily implemented systems and techniques, as well as some techniques requiring considerable engineering development. The principal intent was to provide an early determination of the potential operational effectiveness of several candidate systems and techniques. Accordingly, Phase 1 tests were directed toward three specific objectives:

(1) Determine pilot and aircraft responses to low-level wind shear under baseline conditions--i.e., while conducting precision ILS approach and landing operations in a jet transport airplane that is representative of those in current airline use, with flight crews following established normal operating procedure.

---

*This section was written by Dr. Wade Foy.

(2) Explore differences in pilot and aircraft response to shear under alternative aircraft guidance, control mode, and environmental conditions, to include:

   (a) A conventional non-precision approach using the visual approach slope indicator (VASI) for vertical flight path guidance.

   (b) A non-precision approach incorporating Visual Descent Point (VDP) defined by Distance Measuring Equipment (DME), on the approach segment.

   (c) A coupled approach to Category II weather minimums.

   (d) A takeoff and departure climbout using both full-thrust and reduced-thrust procedures.

(3) Conduct screening evaluations of eight candidate pilot aiding concepts, to include:

   (a) Wind-shear advisories to the pilot, based on ground sensor system data, indicating the expected direction and severity of shear conditions at designated altitudes or segments of the approach.

   (b) A modified approach management technique stressing the use of off-nominal flight situation indications and providing a display of ground speed versus vertical speed for the 3° glide path.

   (c) The availability of Inertial Navigation Systems (INS) wind speed and direction readouts during the approach.

   (d) A panel display of ground speed integrated with the conventional airspeed indicator.

   (e) A panel display of the difference between the along-track wind component on the surface and at the aircraft's present altitude.

   (f) A panel display of flight-path angle (FPA) and potential flight-path angle.

   (g) A head-up display of flight path angle and potential flight-path angle.

   (h) A head-up FPA display incorporating the wind difference indicator (item e above).

The Phase 1 tests were run in April-May 1976 at the Douglas Aircraft Company Flight Crew Training Center, Long Beach, California, using a DC-10 training simulator. These tests were documented in an earlier report.[1*]

---

*References are listed at the end of the report.

The results led to selection of the aiding concepts to be tested in Phase 2, which was designed to examine in detail these potential solutions to wind shear encounters. The objective of Phase 2, therefore, was to evaluate pilot performance during landing operations while using various combinations of wind shear and flight displays. The aiding concepts, incorporating the displays, were to include conventional manual approach management, using a conventional display, as "baseline". The specially developed displays, which were to be either integrated into existing displays or installed within the normal scan pattern of the pilot were:

(1) Ground speed.

(2) Wind difference (i.e., the difference between the longitudinal wind at the aircraft position and the wind along the runway).

(3) Flight path angle.

(4) Flight-director commands incorporating specially modified algorithms using acceleration augmentation.

The approach taken to achieve the objectives of Phase 2 was to conduct a series of piloted flight simulation experiments designed to determine the effectiveness of each aiding concept relative to conventional landing management (baseline) in coping with wind shear. For each display, one or two aiding concepts were developed that specified the technique of pilot use of the display in conjunction with the conventional instruments. In addition, the tests were designed to assess the effects of different types of wind shear, to determine any impact of each special aiding concept on pilot workload relative to baseline, and to obtain pilot assessments of the operational acceptability of the displays and use concepts. The simulation tests were grouped in three experiments involving specific pilot aids, as follows:

Experiment	Aiding Concept
1	Ground speed, analog display by needle on airspeed meter.
1	Ground speed, digital display.

Experiment	Aiding Concept
1	Wind difference, analog command, and digital display.
2	Ground-referenced FPA.
2	Mixed (hybrid, or semi-airmass-referenced) FPA.
3	Modified flight director.
3	Wind difference, analog command.

A task plan for this phase was submitted to the FAA on 5 August 1976 and approved on 12 August.[2] A request for proposal for simulation facility support was issed on 6 August to possible simulator suppliers:[3] Boeing Commercial Airplane Co., Douglas Aircraft Co. of McDonnell-Douglas Corp., and Lockheed California Co. One proposal was received, from Douglas, on 24 August and was evaluated and found acceptable;[4] the simulation subcontract was negotiated with Douglas and start of work was authorized on 20 September. About 1 October, Collins Radio Group of Rockwell International Corp. (Collins) started work on the development of the modified flight-director algorithms. Experiment 1 (evaluation of ground speed and wind difference displays) was run 15-22 November 1976 with eight subject pilots, using 42 hours of simulator time. Experiment 2 (evaluation of flight-path angle displays) was run 13-17 December 1976 with ten pilots and 34 hours on the simulator. Experiment 3 (evaluation of modified flight director control laws) was run 18-27 January 1977 with eight pilots, using 56 hours. In addition, some 7 hours of simulation time were used on 30 November 1976 for demonstrations for visitors from FAA and Lockheed. On 8-10 February 1977, presentations of the Phase 2 results and demonstration runs (about 24 hours) on the simulator were made at Long Beach for visitors from FAA, NASA, USAF, fifteen airlines, Boeing, Douglas, Lockheed, Air Line Pilots Association, Air Transport Association, University of Tennessee, Sierra Research Corp., and the Embassy of Australia.

The AWLS project is under the supervision of Mr. Dean F. Babcock (SRI). The task leader for this Task 2, Phase 2 effort was Dr. Wade H. Foy (SRI). At SRI, Mr. Walter B. Gartner was responsible for the

design of the experiments and also contributed to the development of the aiding concepts and the evaluation of the results; Mr. David W. Ellis was responsible for the data reduction and FPA computer model study; and Mr. Michael G. Keenan was responsible for coordinating the specification of the wind models and also contributed to the evaluation of the results. Dr. A. C. McTee of Bunker Ramo Corp. (BR) was test director for the experiments; Capt. William O. Nice (BR) was the observer for all the experiments and played the role of first officer. Both contributed to the evaluation of the experimental results. At Collins, the development of the modified flight-director algorithms was led by Mr. Jim L. Foster with the assistance of Mr. Larry V. Miller and Mr. E. Dave Skelley. The project manager for the Douglas simulation support program was Mr. John D. McDonnell. The Douglas project pilot was Mr. Art Torosian; Mr. Ernest Admiral was responsible for simulator and test integration, and Mr. Paul L. Jernigan was responsible for simulator software. The program owes much to the enthusiastic cooperation and support of the Douglas team.

The list of pilots who acted as subjects in both Phase 1 and Phase 2 is given in Table 1. They were recruited by the FAA, with the assistance of the Air Transport Association and the Air Line Pilots Association, and they contributed their services without remuneration from the project. This table shows that several of the subject pilots were exposed many times to the particular wind conditions that we simulated, so some degree of " learning the problem" may have been a factor. Notable is the participation of many sectors of the aviation community: FAA Western Region, USAF Military Airlift Command, Boeing, Lockheed, and five airlines. The professional excellence and efforts of these pilots, and the support of their sponsoring organizations, are greatly appreciated.

B. Organization of Report

This Phase 2 effort was directed toward reasonably independent evaluations of the effectiveness of the different aiding concepts, so

Table 1

SUBJECT PILOT PARTICIPATION

Pilot and Affiliation	Spring Tests (Phase 1)	Phase 2 Experiments		
		1	2	3
W. R. Brown, Pan American	X	X		X
W. S. Laughlin, Continental	X		X	
J. L. Menard, FAA	X			
Dick Norman, National	X			X
A. M. Reeser, American	X			
R. W. Reichardt, Continental	X		X	
L. C. Saucke, American	X			
J. E. Smith, FAA	X			
O. E. Attebery, American			X	X
S. M. Carpenter, USAF, MAC		X	X	X
Ralph Cokeley, Lockheed			X	
W. W. Estridge, American		X		
E. C. French, USAF, MAC		X	X	X
J. R. Gannett, Boeing				X
G. A. Hazelhurst, American				X
R. R. Jehlik, Continental		X		
E. W. Johnson, FAA		X	X	X
Ray Lahr, United		X	X	
S. S. Miller, United		X	X	
C. W. Vietor, American			X	

this report is organized according to the separate experiments. The section on "methods," which follows, describes the procedures and conditions (simulator characteristics, wind models and environment, data collected, and briefing and debriefing of subject pilots) that were common to all experiments. Then each of the three experiments is described in a separate section, including the rationale and specification of each aiding concept, the experimental design, the results, and the conclusions drawn. Section VI gives a general discussion of the results and observations for all three experiments, and Section VII contains our recommendations developed from the entire Phase 2 work. Various technical details and supporting documents are in Appendices A through F.

II METHOD*

Phase 2 testing was conducted at the Douglas Aircraft Company's Long Beach facility using the DC-10 Moving Base Research and Development Simulator. Technical support for the test program was provided by key personnel from the Douglas Avionics Engineering and Flight and Laboratory Development subdivisions. This section describes the manner in which the simulation was set up for the experiments and provides an overview of the data collection procedures. More detailed descriptions of the aiding concepts tested and the experimental designs adopted for each experiment are presented in subsequent sections.

A. Simulator Configuration

1. Simulator Cab/and Motion Base

The Moving Base Development Flight Simulator (MBDFS) shown in Figure 1 consists of a modified DC-10 cockpit mounted on a six-degree-of-freedom motion base, and is equipped with a Redifon visual system for representing the external visual scene. DC-10 equations of motion and data acquisition programs were mechanized on a Sigma-5 hybrid computer. The simulation was modified to include specified wind-shear and turbulence models, and the instrument panels were reconfigured to include the experimental displays.

The flight crew compartment contained Captain, First Officer, and Instructor stations. The last, located aft of the Captain's station, was equipped for control of mission start, reset, position freeze, and selection of test conditions. Subject pilots flew the simulated approach sequences from the Captain's station with the basic panel configuration shown in Figure 2. All flight controls, flight instruments, guidance systems, and aircraft subsystems necessary for the performance of the Phase 2 study were provided at the Captain and

*This section was written by Mr. Michael G. Keenan and Mr. Walter B. Gartner.

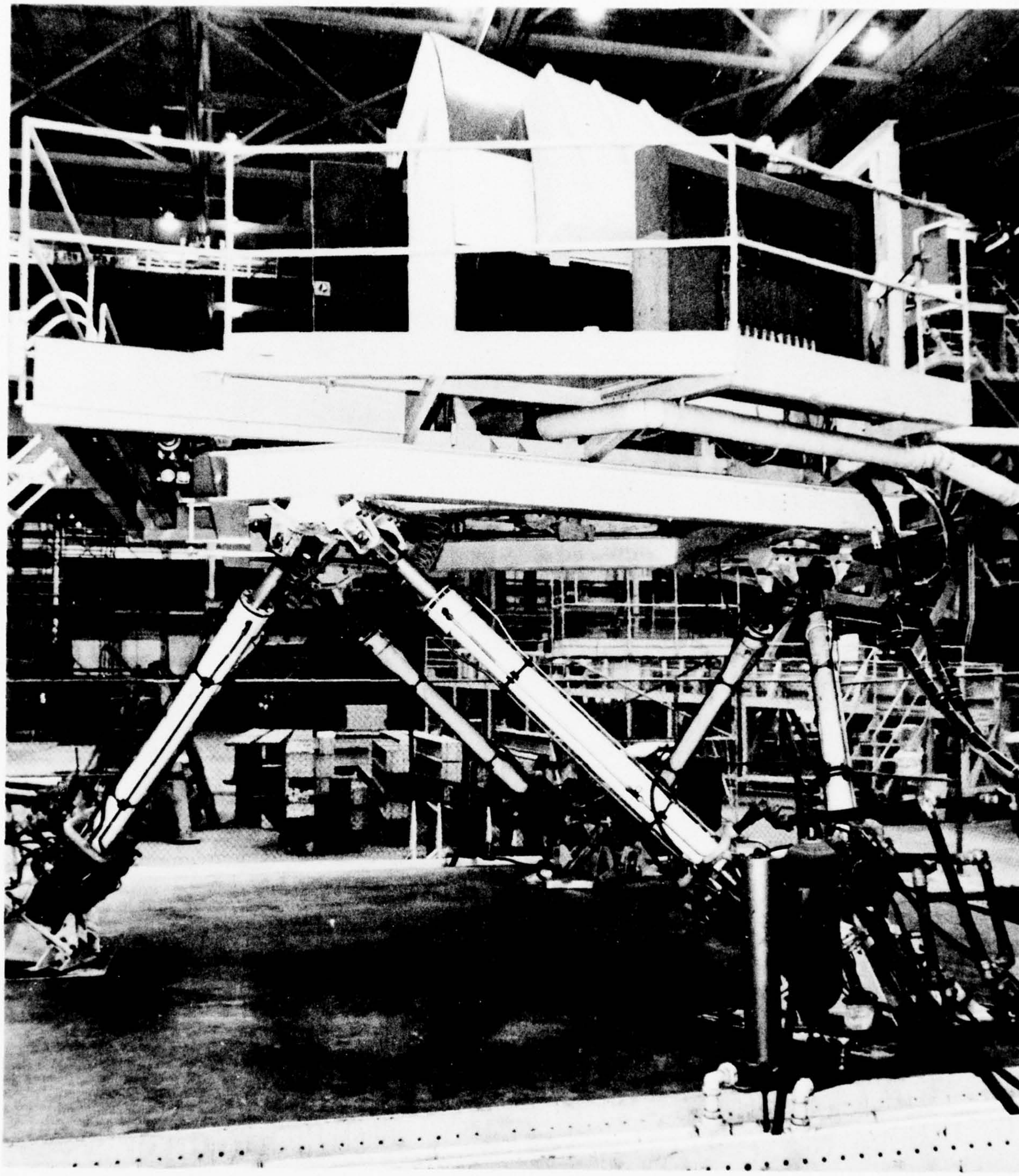


FIGURE 1 MOVING BASE DEVELOPMENT FLIGHT SIMULATOR

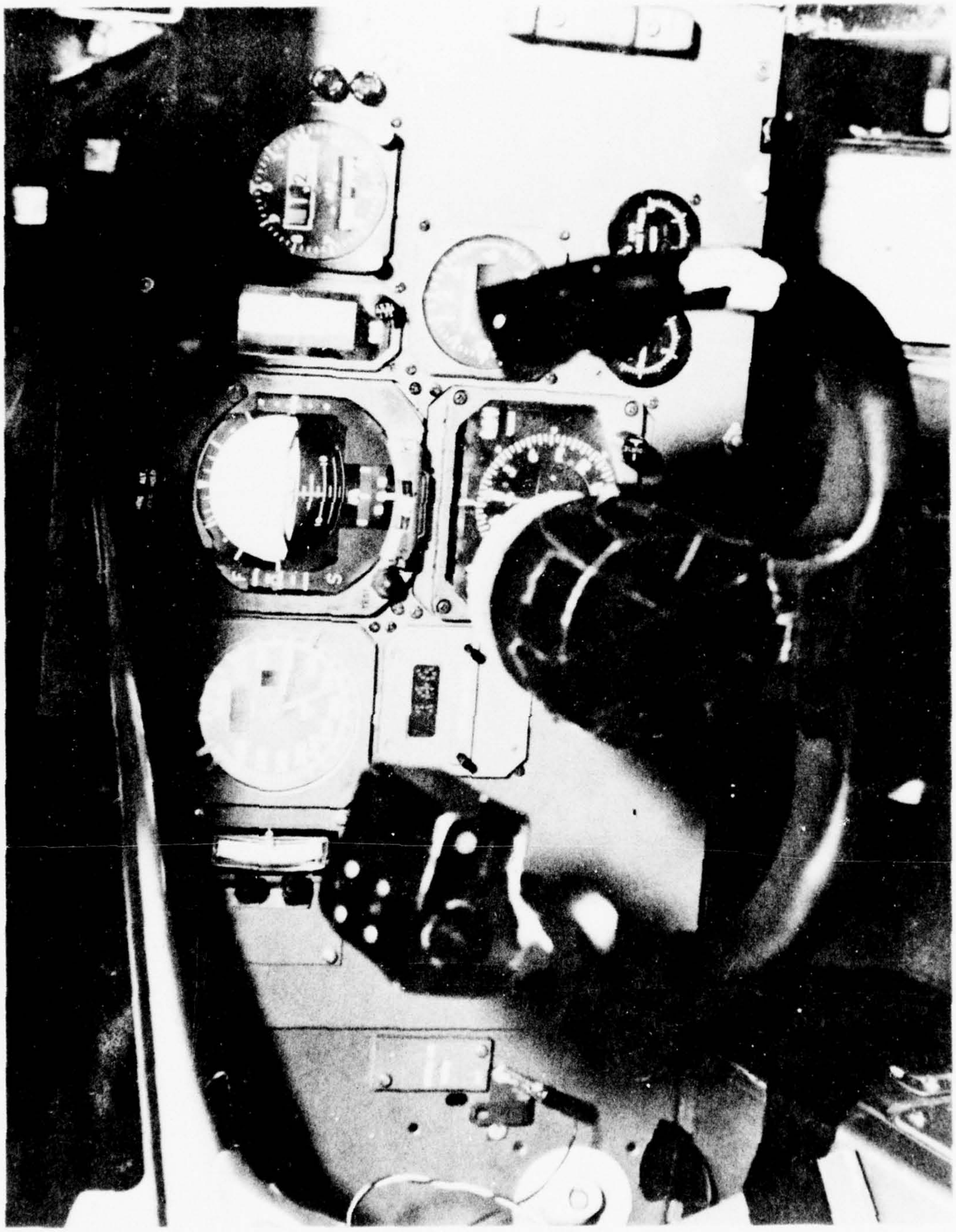


FIGURE 2 SIMULATED DC-10 COCKPIT

First Officer stations and conformed in all respects to those in the DC-10 series aircraft in current use.

The Sigma-5 computer provided program control of data collection and of simulated aerodynamic response, winds, and turbulence, with appropriate parameter values obtained from lookup tables. Wind profiles and turbulence conditions represented in the simulation are discussed in Section II-A-3, below. Digital and analog data were recorded during each simulator run, and at the end of each run a "quick-look" summary was provided.

The external visual scene was generated by a Redifon rigid model system with a scale factor of 750 to 1. The visual scene is represented by a 620-line color television image and displayed by high-resolution monitors viewed through a special Douglas Aircraft asymmetric lens. The Captain and First Officer stations are each equipped with a separate monitor and lens. The visual system has a maximum approach distance of 2.25 miles and an eye altitude range of 725 feet to 15 feet. Approach and strobe lighting were realistically simulated under variable ceiling and runway visual range (RVR) conditions.

The simulator has six degrees of freedom, provided by a six-jack (Franklin Institute) motion base. Motion is controlled from a ground control station located adjacent to the cockpit/platform. Motion capability is summarized in Table 2.

Table 2

SIMULATOR MOTION LIMITS

AXIS	EXCURSION	VELOCITY		ACCELERATION	
		PAYLOAD 20,000 lb	PAYLOAD 3600 lb	PAYLOAD 20,000 lb	PAYLOAD 3600 lb
Heave	±42 in.	±39 in./s	±40.5 in./s	±1.65 g	±1.65 g
Sway	±67.5 in.	±67 in./s	±72.3 in./s	±1.43 g	±2.25 g
Surge	±65 in.	±71 in./s	±71.6 in./s	±1.50 g	±2.6 g
Roll	±30.7°	±35.6°/s	±36.2°/s	±7.8 rad/s²	±7.8 rad/s²
Pitch	±33.3°	±33.6°/s	±32.0°/s	±7.8 rad/s²	±7.8 rad/s²
Yaw	±38.7°	±36.3°/s	±40.3°/s	±7.9 rad/s²	±7.8 rad/s²

2. Aircraft and Runway Simulation

Equations of motion for the DC-10-10 series aircraft were mechanized on the Sigma-5 hybrid computer to provide continuous flight simulation over the low-speed flight envelope. A landing gross weight of 350,000 lb was used in the calculations. Table look-up functions were used for nonlinear aero data such as lift and pitching moments. Ground effects on aero coefficients were simulated over the entire flap range. Nose-wheel steering, differential braking, and landing gear extension-retraction were simulated and nonlinear lateral control spoilers were included. Control surfaces were simulated as either first- or second-order systems with dead zones and position limits included for all surfaces. The simulated runway was 150 feet wide and 10,000 feet long, at sea level, with guidance corresponding to a Category II ILS, 3-degree glide slope. The ILS simulation included beam bends from a table look-up, and beam noise.

3. Wind Profile Simulation

Tables of wind shear and turbulence values were stored in the simulation computer. During each run, these look-up tables were continuously accessed and interpolated to provide wind and turbulence components at the aircraft's current position. These components were summed and input to the aerodynamic equations of motion. Four different wind profiles were used and are hereafter referred to as the "No Shear," "Inversion," "Frontal," and "Thunderstorm" profiles.

The No Shear profile was included as an experimental control condition to obtain data on pilot performance when no significant disturbance was applied. In addition, experience with the wind profiles in Phase 1 testing indicated that pilots could often anticipate a profile by the conditions represented early in the approach. To minimize this recognition factor, the No Shear profiles were designed to resemble two of the shear profiles at the higher altitudes. The two wind profiles used for this purpose are shown in Figures 3 and 4. Shear rates in these profiles are negligible, with maximum rates of 1.33 knots per 100 feet.

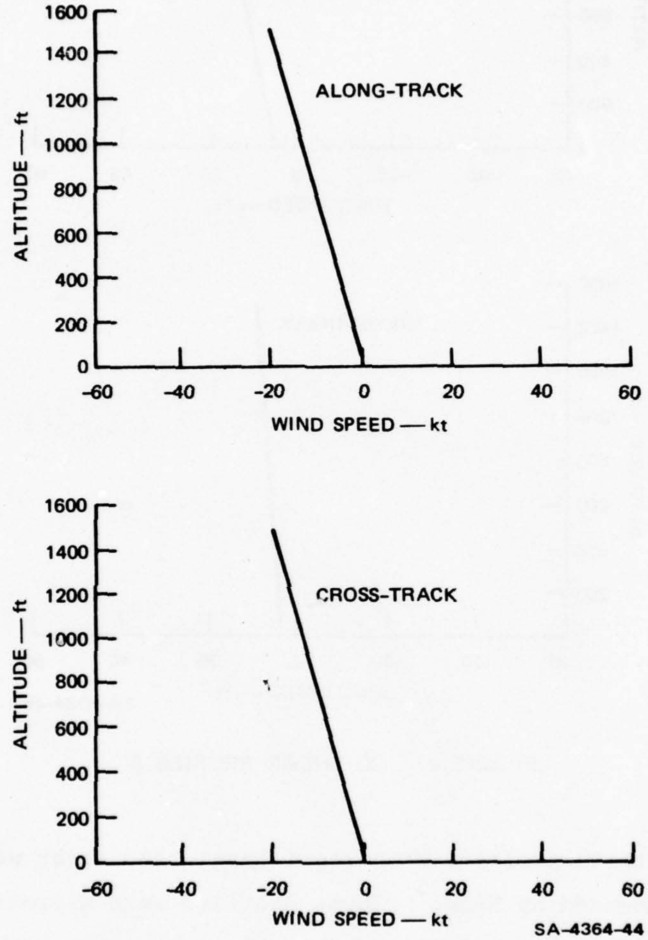


FIGURE 3 NO SHEAR PROFILE A

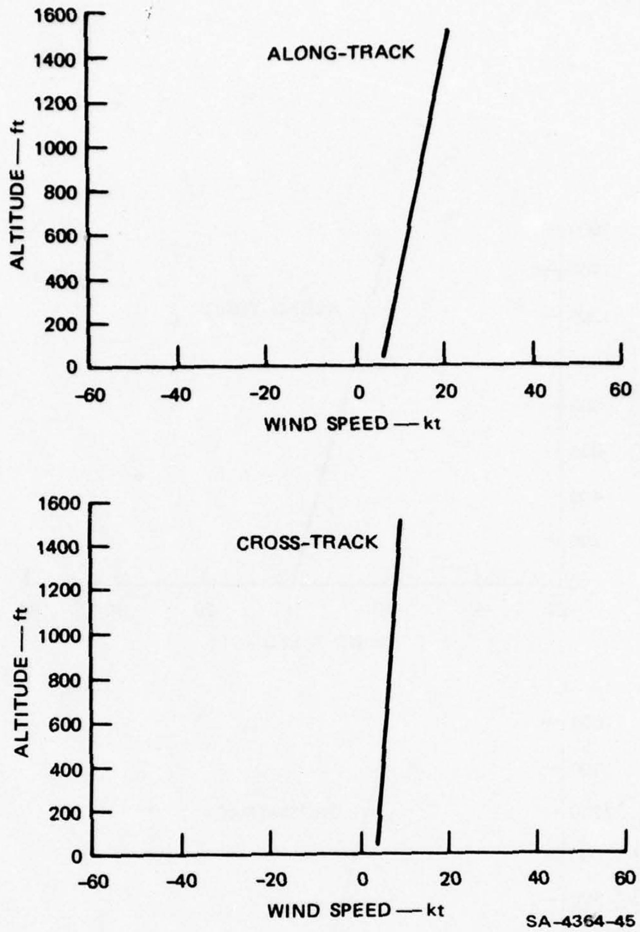


FIGURE 4 NO SHEAR PROFILE B

The three profiles with significant wind shear were based on those recommended by NASA.[5] These profiles were approximately the same as three of those used in the Phase 1 tests, except that the "Thunderstorm" profile here was programmed as a function of both altitude and longitudinal displacement, while in Phase 1 it was a function of altitude only.

The Inversion profile represents shear conditions that might be associated with a nighttime stable boundary layer, wherein a low-level temperature inversion is overlaid by fairly strong winds. This wind profile is shown in Figure 5.

The Frontal profile represents a shear condition associated with a fast-moving frontal zone producing significant turning of the wind vector with altitude. This profile is shown in Figure 6. It is representative of the conditions encountered by Iberian Airlines Flight 933, a DC-10-10, when it crashed on 17 December 1973 at Logan International Airport, Boston, Mass.

The Thunderstorm profile was included to represent the more severe wind shears associated with the "downburst" phenomena described by Fujita[6] in his analysis of the weather conditions encountered by Eastern Airlines Flight 66, a B-727-225, when it crashed on 24 June 1975 at John F. Kennedy International Airport, Jamaica, N.Y. For this profile, wind values were provided as a function of longitudinal distance as well as altitude. This was accomplished by graphical analysis of the diagram of a downburst cell obtained from Fujita's study. The method consisted of extrapolating the streamlines to cover the range of 0 to 1500 feet altitude and 0 to 15,000 feet range, and assuming constant wind speed along the lines. Angles were derived graphically. Wind speed and angle at the desired points were then converted to horizontal and vertical wind components in the X-Z plane. Crosswind components were not derived from Fujita's analysis. A listing of the values that were stored in a computer array and used to compute the three components of wind as a function of aircraft altitude and longitudinal position is provided in Appendix A. For the particular case of an aircraft descending on or close to the nominal 3-degree glide path, the resulting wind profile would be as shown in Figure 7.

Turbulence effects were included in the Inversion and Thunderstorm profiles and were based on use of the Dryden spectra.[7]

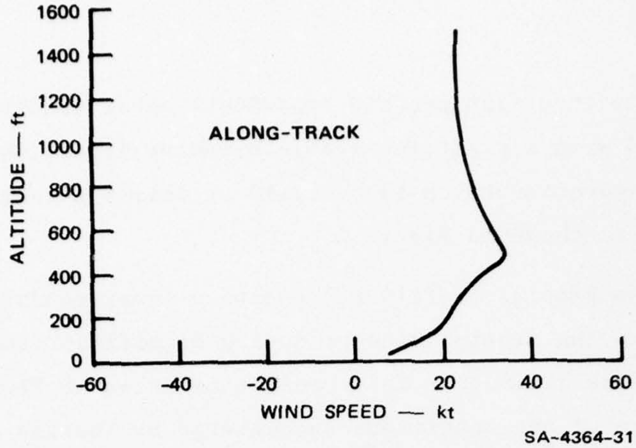


FIGURE 5 INVERSION WIND-SHEAR PROFILE

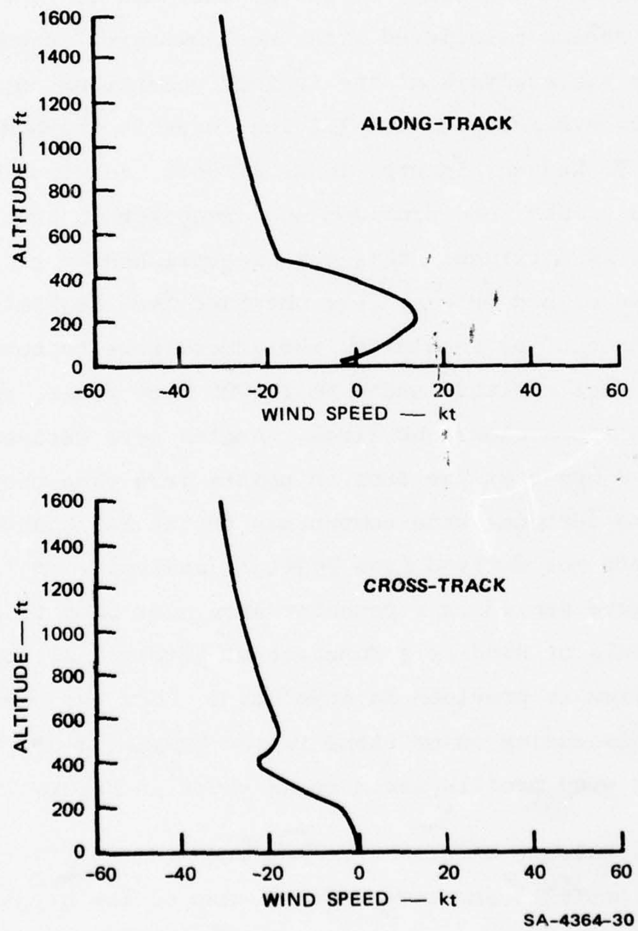


FIGURE 6 FRONTAL WIND-SHEAR PROFILE

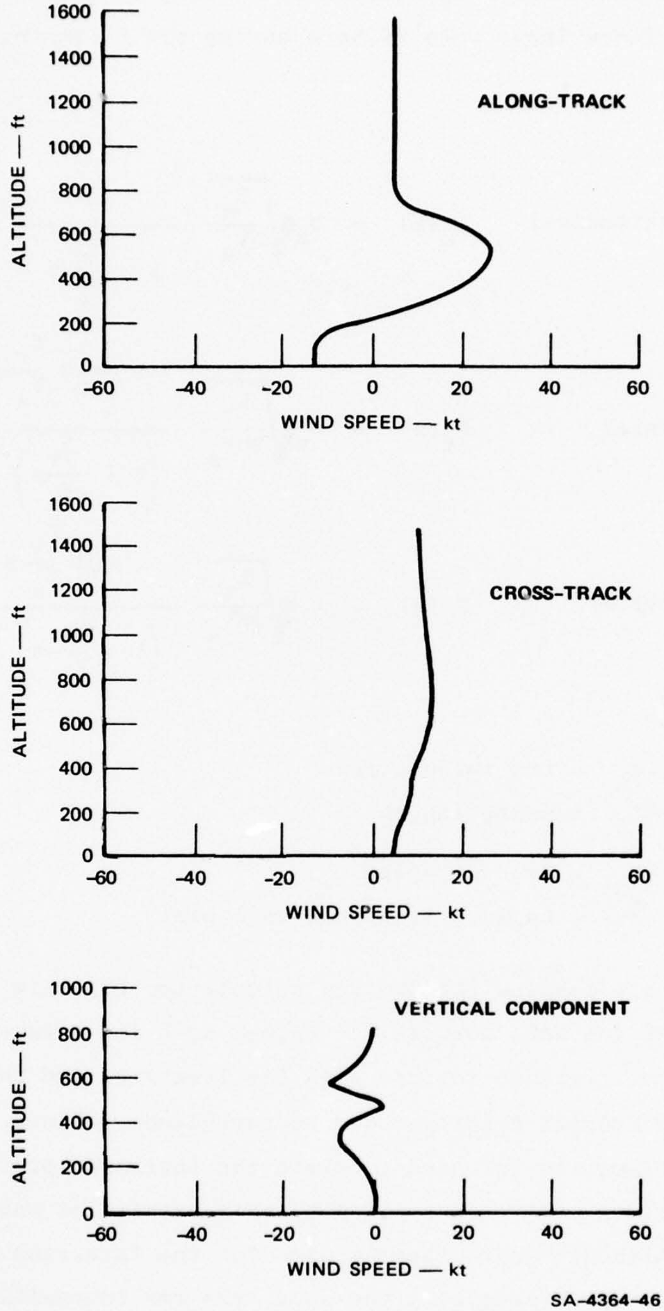


FIGURE 7 THUNDERSTORM WIND-SHEAR PROFILE

Turbulence components were generated by feeding a random, white, zero-mean unit-variance input into filters having the following transfer function:

Longitudinal $$F_u(s) = \sigma_u \sqrt{\frac{L_u}{\pi V_a}} \; \frac{1}{1 + \frac{L_u}{V_a} s}$$

Lateral $$F_v(s) = \sigma_v \sqrt{\frac{L_v}{2\pi V_a}} \; \frac{1 + \sqrt{3}\,\frac{L_v}{V_a} s}{\left(1 + \frac{L_v}{V_a} s\right)^2}$$

Vertical $$F_w(s) = \sigma_w \sqrt{\frac{L_w}{2\pi V_a}} \; \frac{1 + \sqrt{3}\,\frac{L_v}{V_a} s}{\left(1 + \frac{L_w}{V_a} s\right)^2}$$

where

σ_u, σ_v, σ_w = rms intensities

L_u, L_v, L_w = Scale lengths

V_a = True airspeed

s = Laplace transform variable.

Scale lengths (L) and rms intensities (σ) were developed jointly by SRI and NASA workers.[5] Values of L and σ were computed as functions of altitude for use with the Inversion and Thunderstorm profiles; the Frontal condition had no turbulence. Since one of the No Shear profiles was intended to mimic the Inversion profile, similar turbulence values were also applied to this version of the No Shear condition. Although scale lengths used for the Inversion and Thunderstorm profiles are essentially the same, the rms intensities are quite different, consistent with the greatly differing air-mass mechanisms involved. A complete set of the tabulated values for L and σ is given in Appendix A.

B. Evaluation Plan

Phase 2 experiments were designed to determine the improvements in pilot performance of the approach and landing task, in the presence of low-level wind shear, that can be reliably attributed to the use of each of the aiding concepts. A "baseline" condition for making this determination was established by recording pilot performance under identical test conditions using conventional approach management techniques--i.e., using only conventional flight instruments and established operating procedures. As secondary objectives, the evaluation plan also called for pilot assessments of the test display concepts and experimental approach management techniques. The results of this evaluation were intended to support recommendations regarding the continued development, testing, and/or operational application of each aiding concept.

Aiding concepts were evaluated in three separate experiments. Airspeed management techniques based on the use of ground speed and wind difference displays were evaluated in the first experiment, the utility of flight path angle information was examined in the second, and the modified flight director was evaluated in the third. This way of structuring the Phase 2 test program was adopted to accommodate differences in the role of the aiding concept, in the time required to develop the concept for testing, and in the test conditions and evaluation criteria.

1. General Procedures

A standardized project orientation briefing was presented to each subject pilot at the beginning of the first day. This initial briefing covered the objectives of the study, the role of the subject pilot, the general procedure to be followed in the simulator, and the scheduling of simulator sessions. An outline of the content of this briefing and the form used to record pilot background data are presented in Appendix C.

Immediately prior to each scheduled session, pilots were individually briefed on the aiding concept and the approach management

technique to be followed in the simulator. All training and data runs scheduled for a designated aiding concept were completed in a single session lasting approximately one hour. Content outlines for these briefings are presented in Appendix C. The overview of pilot procedures given in the briefing outline for each aiding concept defines the subject's experimental task. During all sessions except the baseline run series, the pre-session briefing stressed the importance of following the prescribed approach management procedure as an element of the aiding concept being evaluated. Pilots were reminded of the fact that the focus of the evaluation was on the aiding concept, and not on their individual skills and proficiency. Debriefing sessions were conducted immediately following each simulator session to allow the pilots to comment on their experiences and to record their critique of the aiding concepts. The set of questions used to guide this debriefing discussion is reproduced in Appendix C.

Simulated approach and landing scenarios were designed to represent a manually flown ILS flight-director approach under Category I weather conditions, with a transition to external visual reference for the landing maneuver. Cloud cover was simulated down to a breakout altitude of 300 feet above runway elevation, with visual conditions after breakout representative of a 2400-feet RVR. Under baseline conditions, subject pilots were briefed to follow standard airline practice for the conduct of the approach, using conventional flight instruments and applying approach management and flight path control techniques as they would in regular line operations. An observer pilot occupied the right seat to perform all normal First Officer duties and provide any special call-outs requested by the subject pilot. When the experimental aiding concepts were used, pilots followed the procedure prescribed in pre-session briefings.

In the first two experiments, pilots were briefed to include the external visual scene in their scan, at their discretion, any time after the First Officer called out that approach lights were in view. In the third experiment, however, they were briefed to stay head down

until they reached 100 feet in order to obtain a more consistent evaluation of the flight-director technique. Since the primary intent of the experiment was to assess the effectiveness of the aiding concepts for completing the approach, pilots were briefed to continue every approach (all three experiments) to 100 feet before initiating a go-around. At any point in the approach where they would have decided to go around, they were asked simply to announce this decision, and the altitude and distance from the runway at this point were recorded.

2. Data Acquisition and Recording

As the approach sequences were executed, 34 flight situation parameters were continuously sampled and recorded on magnetic tape. In addition to this programmed acquisition and storage of digital data, 16 channels of analog data output were recorded on two strip-chart recorders. A detailed description of on-site data recording activity and a listing of the parameters sampled is given in Appendix B.

At the end of each simulator run, a summary data printout was compiled by the computer and was immediately available to on-site test personnel at the line printer. The data content and format of this printout are illustrated in the sample printout reproduced in Figure 8. Elements of the summary data printout indicate the principal types of flight situation data recorded on magnetic tape and include most of the performance measures used to assess the effectiveness of the aiding concepts.

AWLS TASK 2, PHASE 2 SIMULATOR DATA

DATE:	01-18-77	SUBJECT:	1	V(REF):	136.3 KT
TIME:	15:54:13	DISPLAY:	1	V(APP):	144.7 KT
RUN NO:	101	WIND PRO:	1	GNS(REF):	141.3 KT
RUN VL:	1				

GS ALT (FT)	DIST (NM)	VERT OFFSET (FT)	LAT OFFSET (FT)	VERT SPEED (FPS)	LAT SPEED (FPS)	GROUND SPEED (KT)	AIR SPEED (KT)	SUCCESS INDEX (1=T)	
800	-2.51	10.	-9.	-11.6	-.2	161.	148.	1	
500	-1.57	-10.	-17.	-14.2	5.7	154.	146.	1	
200	-.63	6.	-30.	-10.6	4.8	149.	145.	1	
100	-.31	2.	7.	-12.8	1.5	147.	145.	1	
TD	.04	0.	-0.	-5.2	-3.3	143.	137.	1	THE = 5.4 PHI = -1.3

OVER THE 800 FT. TO 100 FT. FLIGHT PATH SEGMENT:

GS DEV (DOTS)		LOC DEV (DOTS)		AIRSPEED DROP (KT)		GR. SPEED DROP (KT)		FPA (DEG)	
MEAN:	.06	MEAN:	-.06	MEAN:	-.04	MEAN:	.00	MEAN:	-3.03
SD:	.20	SD:	.26	MAX:	-.65	MAX:	.00	SD:	3.50

RMS VALUES

VERT OFFSET (FT)	LAT OFFSET (FT)	PITCH STEERING (BW)	ROLL STEERING (BW)	ELEVATOR ANGLE (DEG)	AILERON ANGLE (DEG)
5.7	28.7	.7	1.1	1.1	1.7

GO AROUND (0=NO, 1=SUCCESSFUL, -1=UNSUCCESSFUL): 0
INITIATED AT: .00 NM AT 0. AIRCRAFT HEIGHT

GO AROUND DECISION (0 = NO, 1 = YES): 0
INITIATED AT: .00 NM AT 0. AIRCRAFT HEIGHT

FIGURE 8 SAMPLE SUMMARY DATA PRINTOUT

The top section of the printout identifies the run, the subject pilot, the test conditions, and the appropriate airspeed [V(REF) and V(APP)] and ground speed [GNS(REF)] references for the approach. In the data matrix just below this header information, the values of designated flight situation parameters (column headings) are recorded at various glide slope heights (GS ALT) and at touchdown (TD). Statistics computed over the 800-to100-foot approach segment are then listed to indicate the accuracy of flight path following, the effectiveness of pilot attempts to control airspeed and ground speed drops below reference values, pilot following of flight path angle (FPA) and pitch and roll steering commands, and indications of primary flight control activity (elevator and aileron displacements). The printouts at the bottom of the page provide a record of both actual go-arounds and pilot announcements of go-around decisions. More detailed descriptions of these data elements are also given in Appendix B.

Contrasts between baseline and aiding concept conditions were made primarily on the basis of the relative effectiveness of the pilot's attempts to complete the approach successfully when a designated aid was used. Criterion measures for this assessment were derived from data reflecting approach and landing outcomes and the effectiveness of flight path control and airspeed management during the approach. These performance measures were supplemented by quantitative indicators of pilot workload and acceptance attitudes based on pilot experience with each aiding concept. Pilot workload ratings were obtained immediately following each data run, using a direct estimation technique. For this purpose, workload was conceptualized as "pilot effort," and pilots were asked to indicate the level of effort (mental and physical) they applied to the approach and landing task by placing a mark on a 10cm horizontal line. They were told that higher levels of effort should be indicated by placing the mark nearer to the right end of the line, but no other instructions or guidelines were given for how far along to place the mark or how much effort a given location on the line represented.

Pilot acceptance ratings were obtained in the post-session debriefing sessions. Based on their experience with the displays used, pilots were asked to indicate the level of confidence they would have in their ability to cope with actual low-level wind shear encounters (of the kind they had just been exposed to) using the following five-point rating scale:

(1) Not at all confident. I wouldn't want to have to rely on them.

(2) Uncertain. I'm not sure they would help.

(3) Somewhat confident. I think I could manage some of the shears.

(4) Confident. I could manage most of the shear conditions.

(5) Highly confident. They were a definite help and I'm sure I could cope successfully with any of the shear conditions.

The particular criterion measures used for the assessment of each aiding concept, and their derivation from on-site data records, is discussed in subsequent sections covering each of the three experiments. It should be noted that the basic data records derived from the on-site recording of approach and landing sequences provide a comprehensive data base for case study analysis of aircraft and/or pilot responses to the different wind shear conditions represented in the simulation.

III EXPERIMENT 1: EVALUATION OF GROUND SPEED AND WIND DIFFERENCE DISPLAYS*

Data obtained in the first experiment were intended to satisfy the following objectives:

(1) Determine the improvement, if any, in pilot performance of the approach and landing task when airspeed management is accomplished by reference to ground speed or wind difference displays rather than by conventional techniques.

(2) Identify any difference in pilot performance that may be attributed to the type of shear encountered.

(3) Assess the impact of the use of the experimental displays on pilot workload.

(4) Identify any design features of the experimental displays or associated pilot procedures that might limit their operational utility, effectiveness, or pilot acceptance.

The ground speed and wind difference displays tested in this experiment were designed to provide the pilot with alternative techniques for managing airspeed during the approach. These experimental techniques called for varying approach speeds, based on measured wind effects, and were expected to be more effective in coping with low-level wind shear than conventional constant airspeed techniques. A description of how these displays were represented in the simulation, and of how the subject pilots were briefed to use them is presented next. The design of the experiment is then described and the results are presented and discussed. Conclusions regarding the contrast between the experimental and conventional (baseline) airspeed management techniques are then presented.

---

*This section was written by Mr. Walter B. Gartner.

A. Description of the Aiding Concepts Tested

1. Ground Speed Displays

Two different ways of presenting ground speed information to the pilot were tested. The first display concept, hereafter referred to as GNS-1, is illustrated in Figure 9. This display represents an integration of ground speed with the conventional air speed indicator, using an additional pointer to allow the pilot to monitor both speeds within his normal scan pattern. For Phase 2 testing, the existing V_{mo} (maximum allowable airspeed) pointer was repositioned and driven by a simulated ground speed signal to indicate ground speed in knots on the existing airspeed scale. The ground speed pointer was painted green to clearly distinguish it from the white airspeed pointer.

Pilots were briefed to monitor the relationship between airspeed and ground speed throughout the approach for an indication of the longitudinal wind component affecting the aircraft. By comparing winds aloft with the reported surface wind component, the pilot could estimate the potential for wind shear between his present position and the runway. However, the primary role of this display was to support an airspeed management technique based on pilot selection of a "minimum preplanned ground speed."

Pilots were briefed to adopt a reference ground speed, based on their desired speed at touchdown under reported surface wind conditions, and to manage airspeed throughout the approach so that ground speed would remain at or above this reference value. The reference ground speed was computed by converting the nominal approach speed for a no-wind condition (V_{ref} + 5 knots) to true airspeed and then subtracting the reported surface headwind component. Pilot monitoring of the relationship between indicated and reference ground speed was facilitated by the use of a manually positioned reminder bug, painted green to distinguish it from the conventional white airspeed reminder bugs.

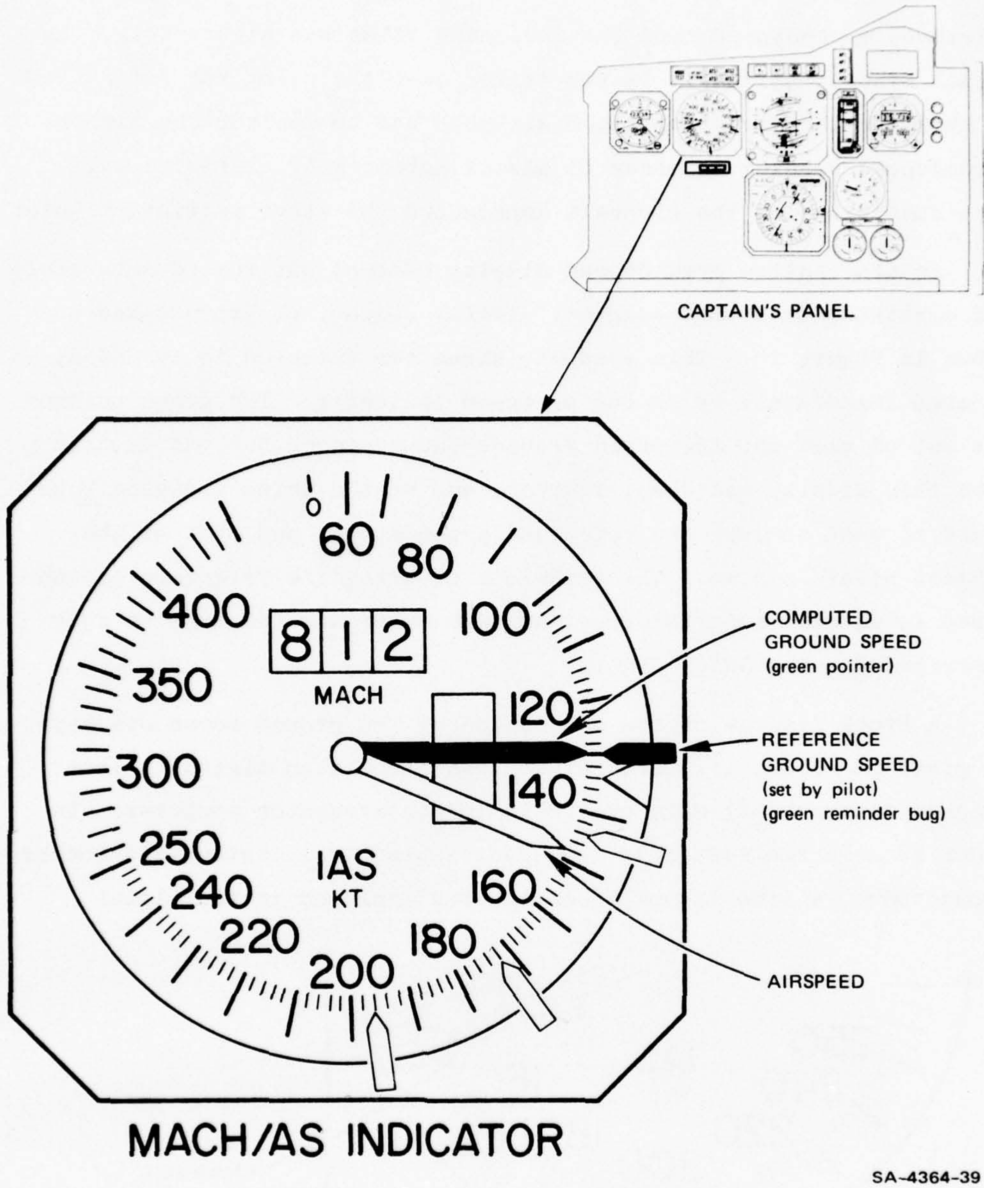


FIGURE 9 PANEL DISPLAY OF GROUND SPEED (GNS-1)

As the aircraft descended on approach, indicated ground speed would change as winds aloft changed. The pilot was instructed to carry additional airspeed as necessary to maintain ground speed at or above the reference marker; however, airspeed would not be reduced below the pilot's target approach speed (V_{ref} + additives) in order to maintain

reference groundspeed when the indicated value was higher (e.g., in a tail wind situation). In the latter case the pilot was instructed to maintain the target approach airspeed and to monitor the higher groundspeed reading in order to assess potentially excessive tail wind conditions as the aircraft approached the flare initiation point.

An alternative groundspeed display concept was tested separately and consisted of a three-segment digital readout of groundspeed as shown in Figure 10. This readout, hereafter referred to as GNS-2, was located immediately below the airspeed indicator. The green pointer was out of view and the green groundspeed reminder bug was omitted when this display was used; however, one of the white airspeed bugs could be used to mark the reference groundspeed, and most of the subject pilots did so. The technique of using the reference groundspeed as an additional minimum approach speed was the same as that described for the GNS-1 display.

A block diagram of the derivation of the ground speed displays is given in Figure 11. Groundspeed was calculated digitally from sampled distance (X) data available in the simulator computer. In order to more realistically represent a practical instrumentation of groundspeed, a time lag of 5 seconds was included in the signal

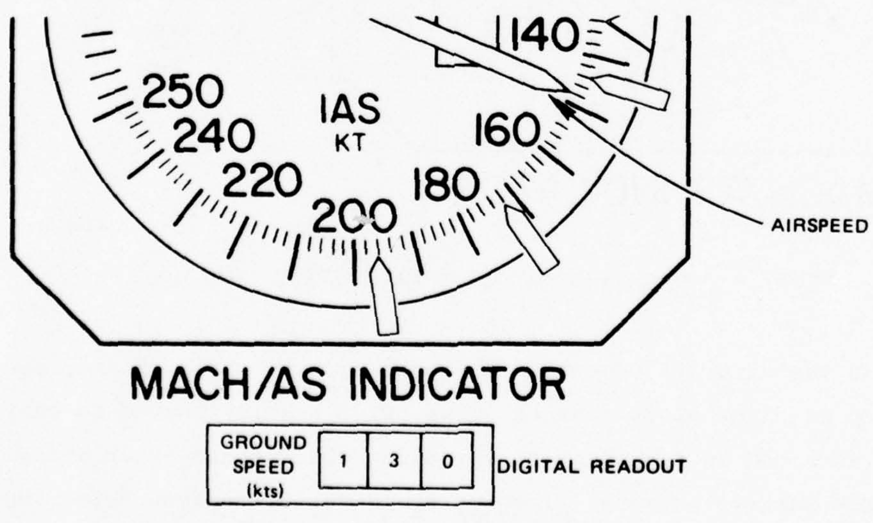


FIGURE 10 ALTERNATIVE DISPLAY OF GROUND SPEED — DIGITAL READOUT (GNS-2)

processing. To accomplish this in the simulation, a digital equivalent of an analog filter having the following characteristic was implemented:

$$\frac{GS}{X} = K_o \frac{s}{1 + \tau s}$$

where

τ = 5 seconds

K_o = 0.5925 (knots/feet/seconds)

s = Laplace transform variable

GS = Measured ground speed (knots)

X = Longitudinal position (feet)

Provisions were made in the simulator cab for manual selection of the ground speed signal to drive either the green pointer on the air-speed indicator or the digital display, as shown in Figure 11. Appropriate selections were made prior to each test run, in accordance with

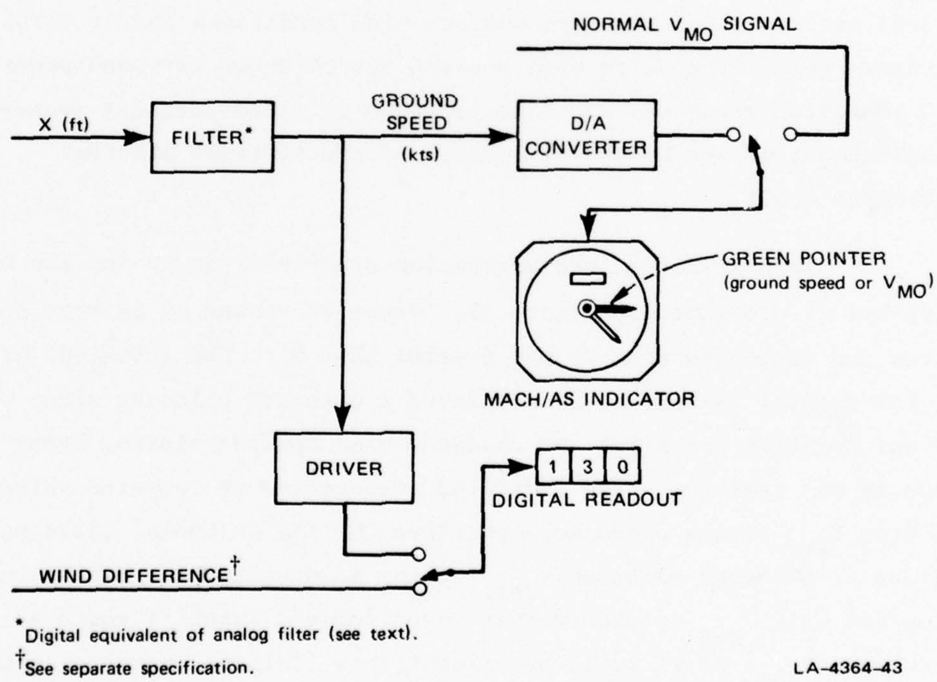


FIGURE 11 DERIVATION OF DRIVE SIGNALS FOR TEST DISPLAY OF GROUND SPEED

the run schedule. Inputs to the airspeed indicator were either ground speed or the normal V_{mo} signal input. Inputs to the digital readout were either ground speed or a "wind difference" signal described in the next section.

2. Wind Difference Displays

Wind difference (ΔW) information was derived from the relationship between the longitudinal wind component affecting the aircraft (W_a) and the along-track surface wind component (W_s). A positive value of either component represents a headwind condition and a negative value is a tail wind. The quantity ΔW is the difference between W_s and W_a and was computed continuously and displayed on the digital indicator immediately below the airspeed indicator, as shown in Figure 12. ΔW was also subtracted algebraically from the reference approach speed established for the aircraft at a given gross weight (V_{ref}) to derive a command airspeed (CMD IAS). Prior to display, CMD IAS was compared with the pilot-selected target approach speed (V_{app}), which includes airspeed additives to V_{ref} that the pilot considers necessary for reported surface wind conditions and/or turbulence. Airspeed error (the difference between the ΔW-based airspeed command and indicated airspeed) was also provided in a conventional manner as displacement of the Fast-Slow pointer on the Attitude Director Indicator (ADI).

An overview of the derivation of drive signals for the ΔW displays is presented in Figure 13. Negative values of ΔW were computed and displayed when W_a was greater than W_s. The left-most window of the digital readout of ΔW displayed a downward pointing arrow when ΔW was negative (or zero) and changed to an upward pointing arrow when ΔW was positive. The indicated subtraction of computed values of ΔW from V_{ref} always produced a positive CMD IAS in knots, since positive values of ΔW never exceeded V_{ref}. Prior to display, the CMD IAS was compared with V_{ref} to ensure that the displayed quantity would not be less than V_{app}, as it would be without this limiting operation when ΔW was positive (or when negative values of ΔW were less than pilot-selected speed additives).

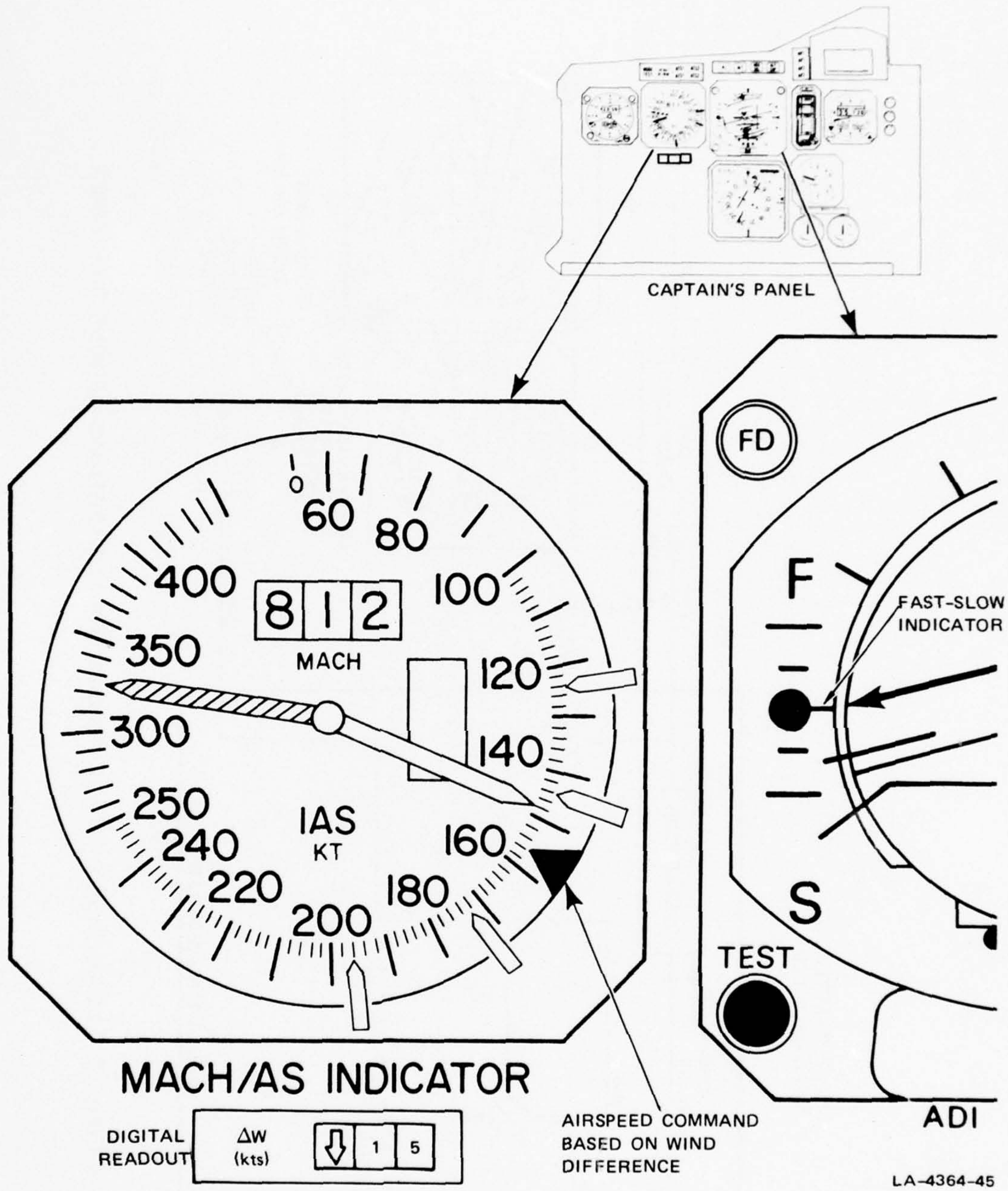


FIGURE 12 PANEL DISPLAY OF WIND DIFFERENCE

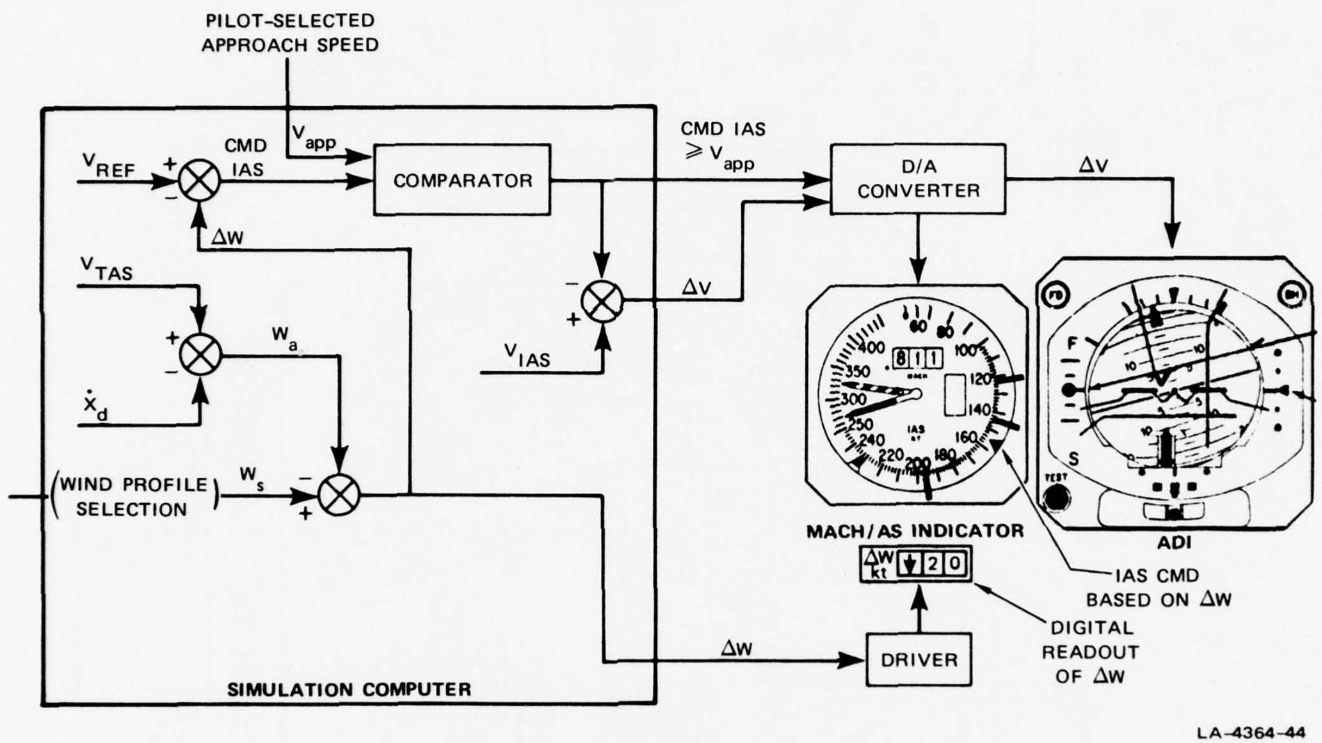


FIGURE 13 DERIVATION OF DRIVE SIGNALS FOR TEST DISPLAYS OF WIND DIFFERENCE

After the necessary digital-to-analog conversion, the CMD IAS signal was used to drive the existing command airspeed bug on the airspeed indicator. Scaling is the same as the drive signal for indicated airspeed for the 2-knot-per-scale-marker range of airspeeds (100 to 250 knots). The CMD IAS signal was provided as an alternative way of positioning the command airspeed bug; the conventional inputs were available on a selective basis when required for other display configurations. The Fast-Slow pointer on the ADI was driven by an error signal based on the CMD IAS (ΔV) and is simply indicated airspeed minus CMD IAS in knots. Positive values of ΔV produced an upward deflection of the pointer (Fast) and negative values displaced it downward (Slow). Scaling of this display was the same as that used for conventional speed command displays.

When the ΔW displays were used, the subject pilots were briefed on the interpretation of the ΔW readout and instructed to follow the airspeed command as closely as they could throughout the approach. Early in the approach, the ΔW readout could be used as a direct indication of potential wind shear and the potential effect on airspeed. A negative (arrow down) readout alerted the pilot to a comparatively lower head wind component on the ground and could be interpreted as an indication of eventual airspeed loss. Positive readouts (arrow up) indicated a comparatively greater head wind component on the ground and a potential increase in airspeed. The pilot's primary task, however, was to follow the ΔW-based airspeed command and to use the digital readout only to cross-check the appropriateness of the command information.

B. Experimental Design

1. Subject Pilots

The eight subject pilots recruited by FAA for the first experiment included five currently active airline pilots, one FAA pilot currently engaged as an air carrier operations inspector, and two U.S. Air Force pilots from the Military Airlift Command. Three of

the airline pilots were DC-10 rated with more than 2000 hours in the airplane. All of the airline pilots were senior Captains with more than 15,000 hours of pilot-in-command time. The FAA pilot reported 6700 command pilot hours with $2\frac{1}{2}$ in the DC-10. One of the USAF pilots reported 5500 total flying hours and was C-141 qualified and the second reported 1000 hours as pilot-in-command and was currently flying the C5A.

2. Pilot Assignment to Test Conditions

A repeated measures design was used that called for each subject pilot to fly all combinations of aiding concept and wind shear conditions. The principal advantage of this design is that variability in the criterion measures due to differences between pilots can be sorted out in the data analysis and thereby provide a more sensitive test of the differences between baseline and aiding concept conditions. The principal disadvantage is that the data may be biased by pilot motivation, fatigue, or learning effects that carry over from one condition to another. These carry-over effects were partially controlled by counterbalancing the order in which the pilots were exposed to the baseline and aiding concept conditions.

Simulator run schedules developed for implementing the experimental design established the order in which each subject was exposed to the 16 Aiding-Concept-by-Wind-Profile combinations. For convenient reference, each of the four subsets of data runs for a designated aiding concept were distinguished as a "run series." Each run series consisted of eight approach and landing sequences per pilot, two for each of the four wind profiles. Table 3 shows the order in which each pilot was assigned to each run series to control for carry-over effects.

The order in which subjects were exposed to the four wind profiles was randomized within the 8-run series, and the pattern of

Table 3

ORDER OF SUBJECT PILOT ASSIGNMENT
TO AIDING-CONCEPT CONDITIONS

Subject Pilot	Run Series			
	1st	2nd	3rd	4th
1	Baseline	GNS-1	GNS-2	ΔW
2	Baseline	ΔW	GNS-2	GNS-1
3	ΔW	GNS-2	GNS-1	Baseline
4	GNS-2	Baseline	ΔW	GNS-1
5	ΔW	Baseline	GNS-1	GNS-2
6	GNS-1	ΔW	Baseline	GNS-2
7	Baseline	ΔW	GNS-1	GNS-2
8	ΔW	Baseline	GNS-1	GNS-2

variation was the same for each run series. This randomized pattern is given in the following listing:

Run	Wind Profile
1st	Frontal
2nd	No shear
3rd	Thunderstorm
4th	Inversion
5th	Thunderstorm
6th	No shear
7th	Inversion
8th	Frontal

Prior to each data run series, subject pilots flew one approach sequence under unrestricted visual conditions for simulator and aiding concept familiarization. They then completed a four-run training series in simulated Category 1 weather to practice the experimental task. During the training series, each of the four wind profiles was applied in turn.

C. Results and Discussion

1. Approach and Landing Outcomes

The aiding concepts evaluated in the first experiment represent alternative ways of managing airspeed during the approach segment from glide slope capture down to a point just prior to flare initiation where the pilot's attention is primarily on external visual cues and he is no longer using the panel instruments. The principal indicator of the relative effectiveness of these experimental techniques is an overall index of approach outcomes derived from the aircraft's flight path offsets and rate of descent as it passed the Inner Marker (i.e., a position corresponding to a glide slope height of 100 feet). An approach was counted as within limits only when the following values of flight-path displacement and rate of descent were not exceeded:

(1) Vertical offset from the glide slope was within ±28 feet (two dots).

(2) Lateral offset from the extended runway centerline was within ±75 feet (nominal runway width).

(3) Rate of descent was 1500 feet per minute or less.

The landing maneuver is defined as the flight segment bounded by flare initiation and touchdown on the runway. The experimental airspeed management concepts do not directly support pilot performance of this maneuver, and touchdown performance is affected by other factors such as pilot use of the simulated visual cues and his proficiency in landing technique for the aircraft simulated. Nevertheless, landing outcomes were examined as an indirect measure of the effectiveness of the aiding concepts. Touchdowns were counted as within limits when the following values of touchdown position, rate of descent, lateral velocity and aircraft attitude were not exceeded:

(1) Main gear contact occurred within the touchdown zone from threshold to 3000 feet down the runway and with the aircraft CG within ±50 feet of the runway centerline.

(2) Rate of descent was 10 feet/second or less.

(3) Lateral velocity was less than 14.5 feet/second.

(4) Pitch attitude was at least one degree nose-up and not greater than 13 degrees.

(5) Roll attitude was less than ±9 degrees.

Contrasts between baseline (BL) and aiding concept performance are represented graphically in Figure 14. Data points in this summary plot are the proportion of within-limits approach and landing outcomes relative to the total number attempted under each designated wind profile condition by the eight subject pilots. In deriving the proportion within limits at 100 feet, a missed approach initiated above 100 feet was counted as outside limits without regard to recorded flight-path offsets or vertical speed at the Inner Marker. A go-around below 100 feet was counted as an out-of-limits touchdown.

Figure 14 shows substantial improvement in approach outcomes only for the ground speed pointer (GNS-1) technique. Pilot management of the Frontal and Thunderstorm shear encounters using this technique is at about the same level as the No Shear condition, indicating the potential effectiveness of this technique for managing the more severe wind shear effects. Differences between baseline and GNS-1 approach outcomes for the Frontal and Thunderstorm wind profiles, as tested by the Cochran Q test[8] are significant at less than the 0.05 probability level. Differences between baseline and the digital ground speed (GNS-2) or wind difference (ΔW) techniques for the same wind profiles are not statistically significant.

A smaller proportion of within-limit approach outcomes, relative to baseline, is shown for the No Shear condition for all aiding concepts and a substantially smaller proportion is shown for the ΔW technique. This finding suggests that the attempt to incorporate a new instrument or different airspeed control technique into conventional approach management practices produced some degradation to pilot performance of the basic flight path control task. The more pronounced effect recorded for the ΔW technique may be due to the comparatively greater lack of pilot familiarity with the wind difference concept relative to the use of ground speed.

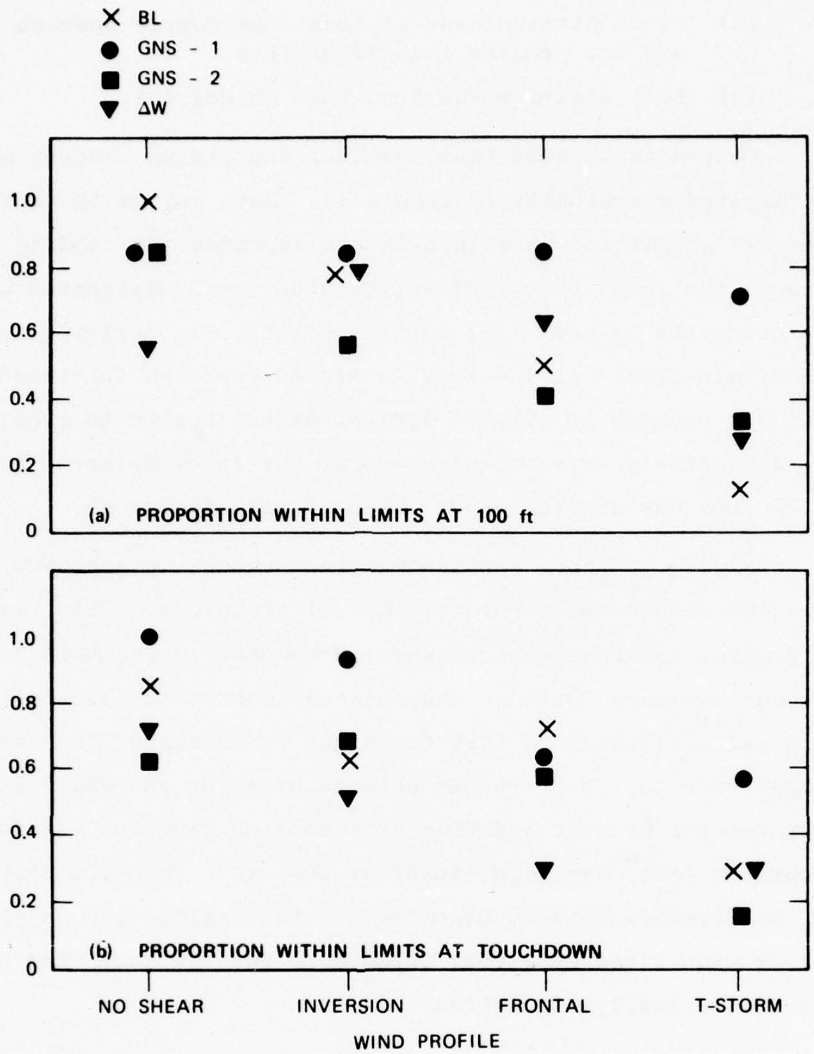


FIGURE 14 SUMMARY OF APPROACH AND LANDING OUTCOMES FOR ALTERNATIVE AIRSPEED MANAGEMENT TECHNIQUES

Landing outcomes are summarized in Figure 14(b) and show a similar pattern, with substantial improvement over baseline performance recorded only when the GNS-1 technique was used. Differences between baseline and GNS-1 for the Inversion and Thunderstorm profiles are significant at better than the 0.05 level. Notice that a substantially greater number of out-of-limits touchdowns were recorded for the ΔW technique against the Frontal profile. During most of the approach

under this wind condition, the aircraft is experiencing a tail wind, ΔW is positive, and no airspeed pad is commanded. An abrupt tail-to-head wind shear occurs below 450 feet and perhaps the ΔW technique does not provide an indication of this type of shear effect early enough to be helpful.

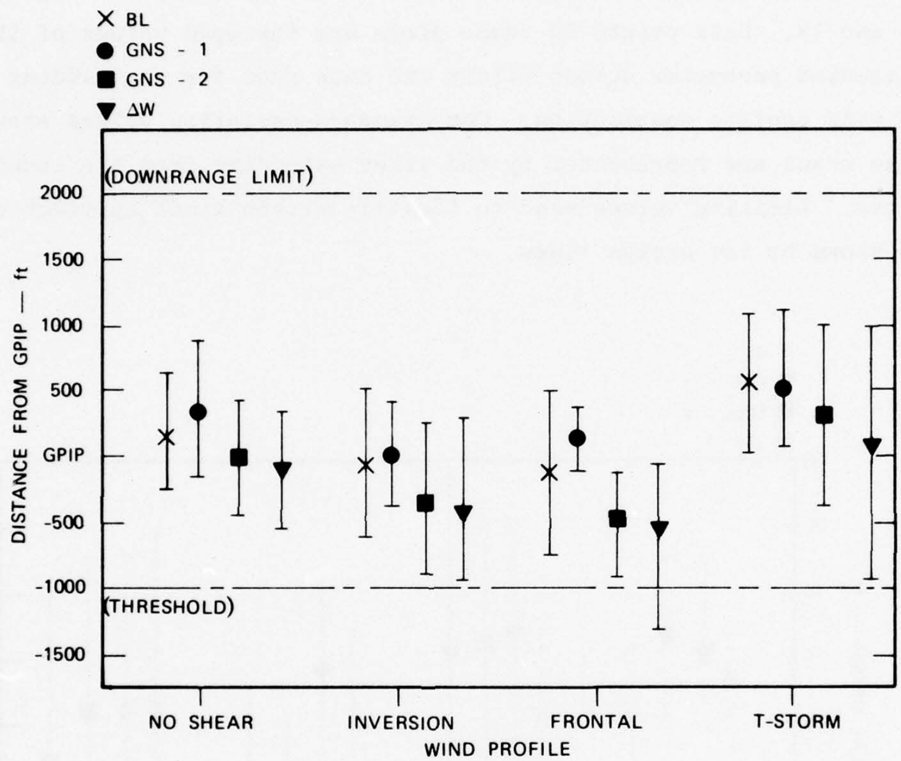


FIGURE 15 TOUCHDOWN POSITION ALONG THE RUNWAY

Touchdown positions along the runway are summarized in Figure 15. Coded data points are mean touchdown positions, across pilots, relative to the glide-path intercept point (GPIP). One-standard deviation values around these means are represented by the lines extending above and below the data points. Except for the trend toward shorter touchdowns when the GNS-2 and ΔW technique were used, no substantial differences in touchdown position are indicated. Touchdown data were not available, of course, when a go-around was executed.

Since the number of go-arounds differed across wind profiles, the mean touchdown positions are necessarily based on different numbers of runs.

Summary data plots for the three flight situation parameters that define approach outcomes at 100 feet are presented in Figures 16, 17, and 18. Data points in these plots are the mean values of the designated parameter across pilots and data runs for each aiding concept and wind profile combination. One-standard-deviation values around these means are represented by the lines extending from the coded data points. Limiting values used to identify within limit approach outcomes are shown by tne broken lines.

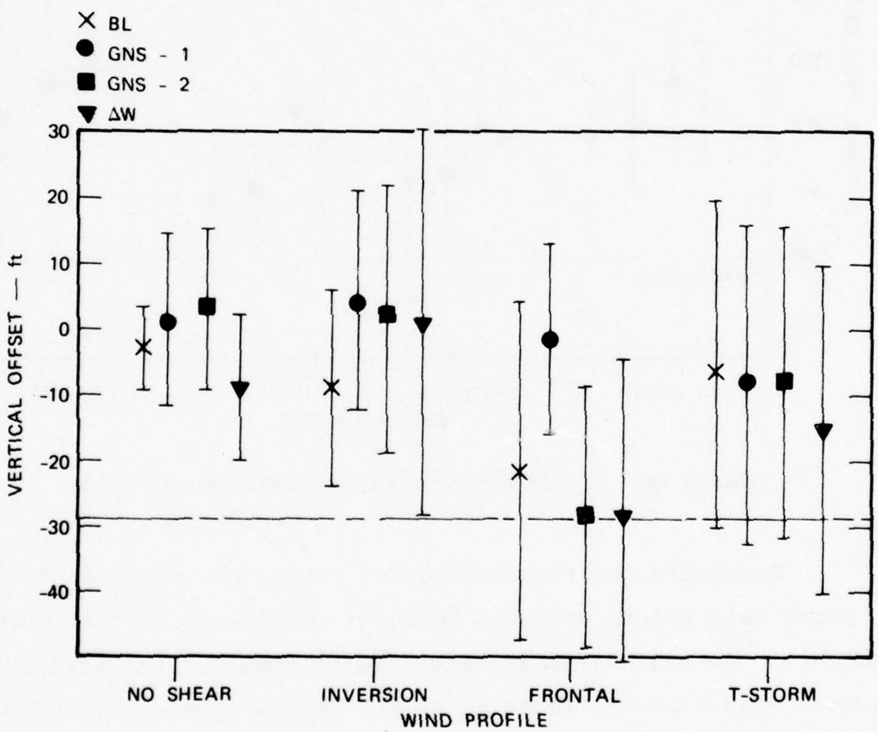


FIGURE 16 MEAN AND STANDARD DEVIATION OF GLIDE PATH DISPLACEMENTS AT THE INNER MARKER

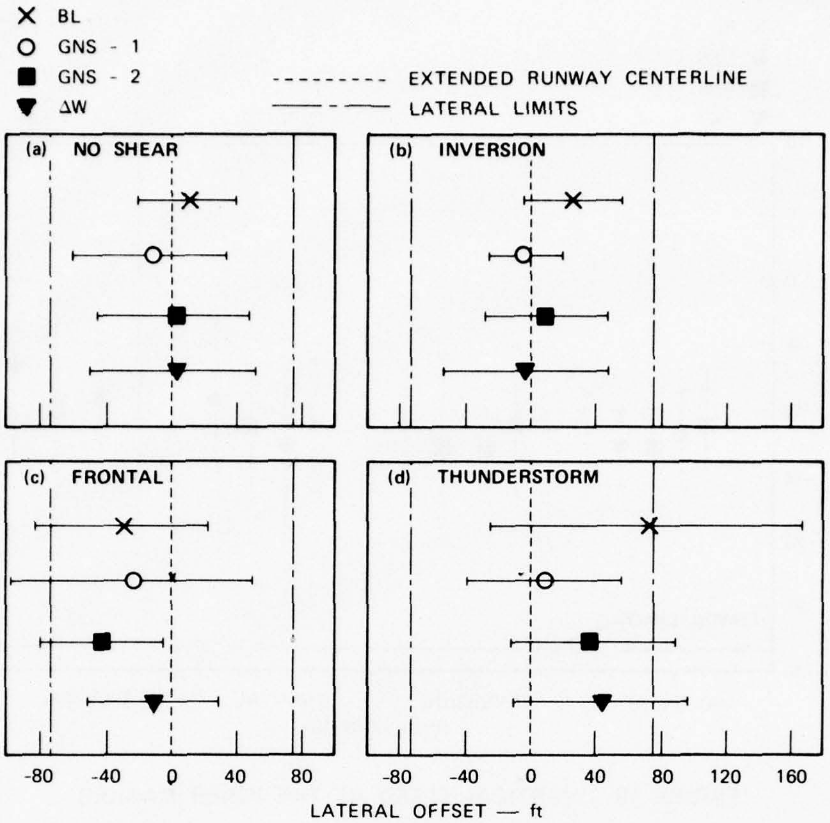


FIGURE 17 LATERAL DISPLACEMENT AT THE INNER MARKER

Significant differences between baseline and aiding concept performance were indicated only for vertical offset at the Inner Marker. Figure 16 indicates that vertical offsets are generally within limits on all wind profile conditions except the Frontal shear. Under this condition, only the GNS-1 technique produced within-limit vertical offsets. Differences between baseline and aiding concept performance for each wind profile were tested using Dunnett's t statistic for comparing treatment means with a control.[8] Statistical significance at the 0.05 level was reached only for the contrast between baseline and the GNS-1 technique under the Frontal shear condition.

Mean vertical speeds and lateral offsets at the Inner Marker recorded for each aiding concept (Figures 17 and 18) do not differ signi-

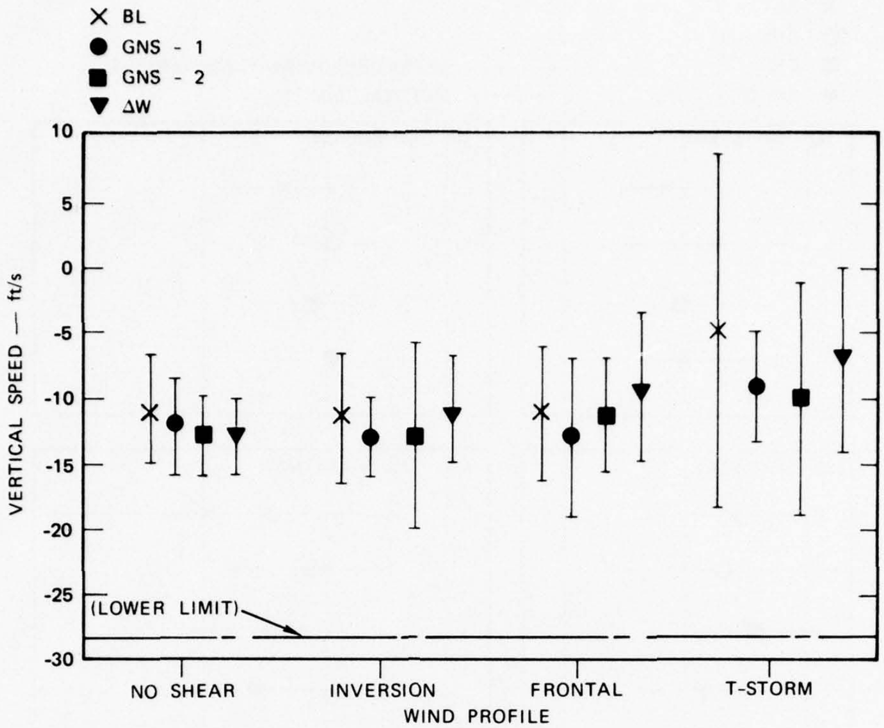


FIGURE 18 VERTICAL SPEED AT THE INNER MARKER

ficantly from baseline approach outcomes for any of the wind profiles. One sigma variations in vertical speed were above the 25-foot/second lower limit for all aiding concepts on all wind profiles, with greater variability indicated for the Thunderstorm condition.

Scatter plots of approach-outcome positions for Frontal and Thunderstorm profiles are given in Appendix F.

2. Airspeed Management

The primary role of the ground speed and wind difference displays was to support pilot performance of the airspeed management task. In accordance with the use concepts tested, effective airspeed management means that indicated airspeed does not drop below pilot-selected target approach speeds and, for the GNS-1 and GNS-2 tests, that ground speed does not drop below the minimum preplanned speed. An

indication of how well the pilots were able to carry out this task is provided by the data presented next.

Figure 19 shows that the pilots were not fully successful in maintaining the reference ground speed over the 800-to-100 foot approach segment, although they did manage to keep the speeds up to within about 10 knots of reference when the aiding concepts were used. Using conventional (baseline) airspeed management techniques, ground speed drop averaged more than 25 knots below reference during the Inversion and Thunderstorm shear encounters. Both of these shears entail a substantial headwind shearout under 500 feet.

Figure 20 shows that the technique of maintaining the reference ground speed did effectively counter the airspeed loss that would otherwise be experienced in the Inversion and Thunderstorm shears, particularly in the latter case. Average airspeed loss (relative to pilot-selected target approach speeds) during the Thunderstorm shear was at about 13 knots for baseline and well below 5 knots when reference ground speeds were maintained.

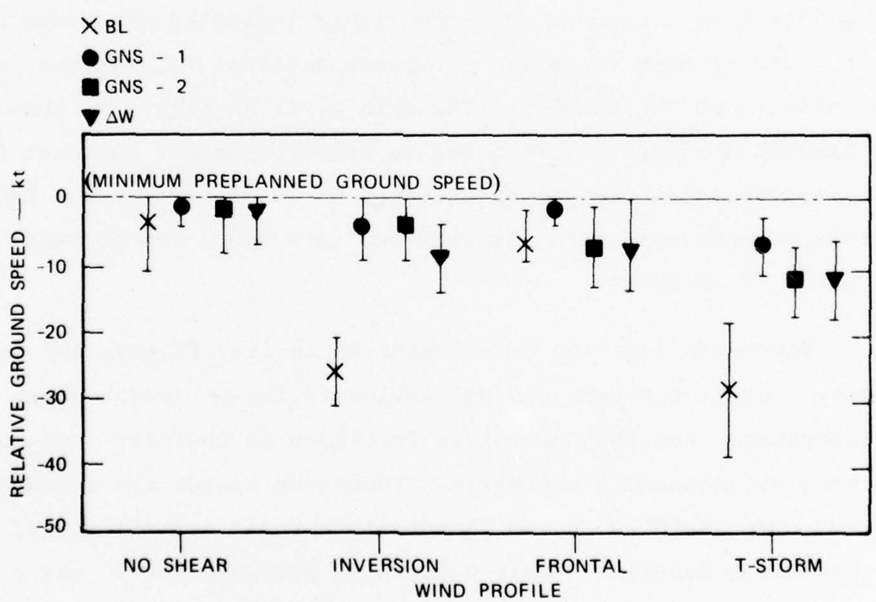


FIGURE 19 MAXIMUM DROP IN GROUND SPEED OVER THE 800-TO-100-FOOT APPROACH SEGMENT

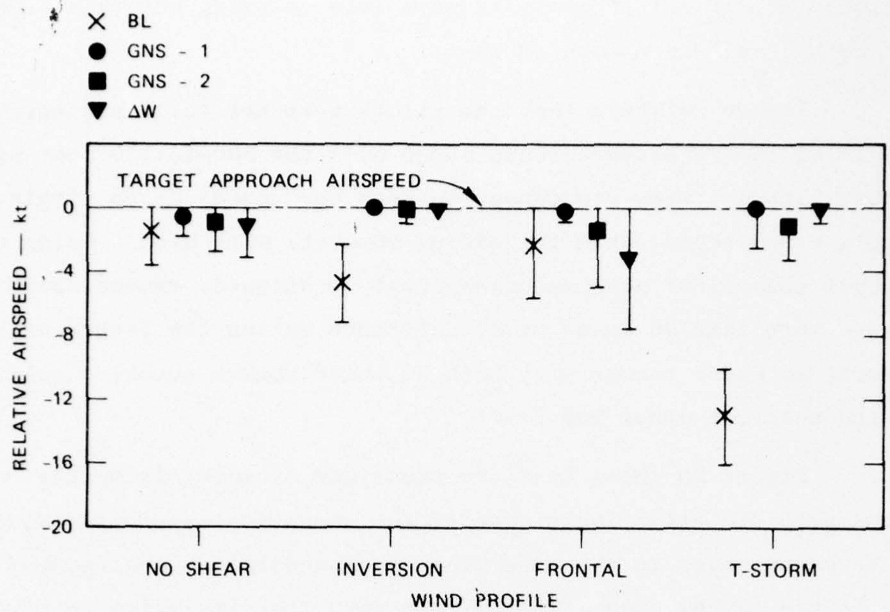


FIGURE 20 MAXIMUM DROP IN INDICATED AIRSPEED OVER THE 800-TO-100-FOOT APPROACH SEGMENT

In their initial exposure to the ground speed and ΔW techniques pilots were concerned that the higher indicated airspeeds on approach would produce excessive airspeeds at flare initiations, with adverse effects on the landing. The data plots in Figure 21 show higher indicated airspeeds, relative to selected target approach speeds, when the experimental techniques are used on the Inversion and Thunderstorm shears. Averaged across pilots and data runs, the increase is on the order of 12 knots.

Touchdown position data presented earlier (Figure 15) suggest that these excessive speeds did not seriously impact longitudinal touchdown dispersions, and the data plots in Figure 22 indicate that touchdown speeds were not generally excessive. Touchdown speeds are somewhat higher and more variable on the Thunderstorm shear for all aiding concepts, including baseline. This outcome is probably due to the effects of the substantial thrust increase required on the low end of the approach in order to get through this shear encounter to a successful touchdown.

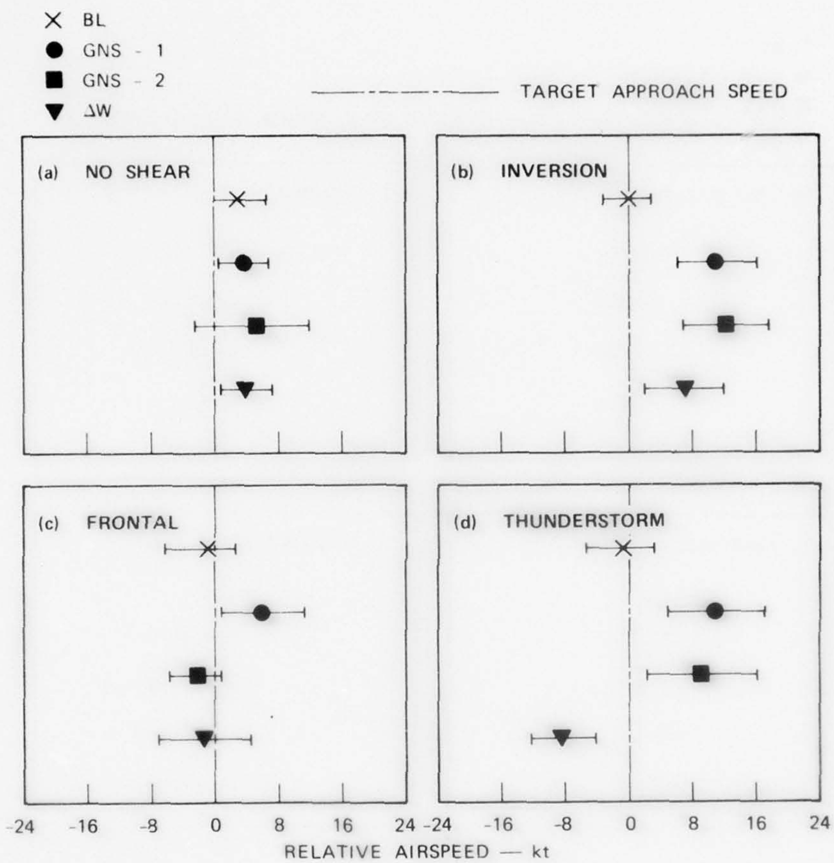


FIGURE 21 DIFFERENCE BETWEEN INDICATED AIRSPEED AND TARGET APPROACH SPEED AT THE INNER MARKER

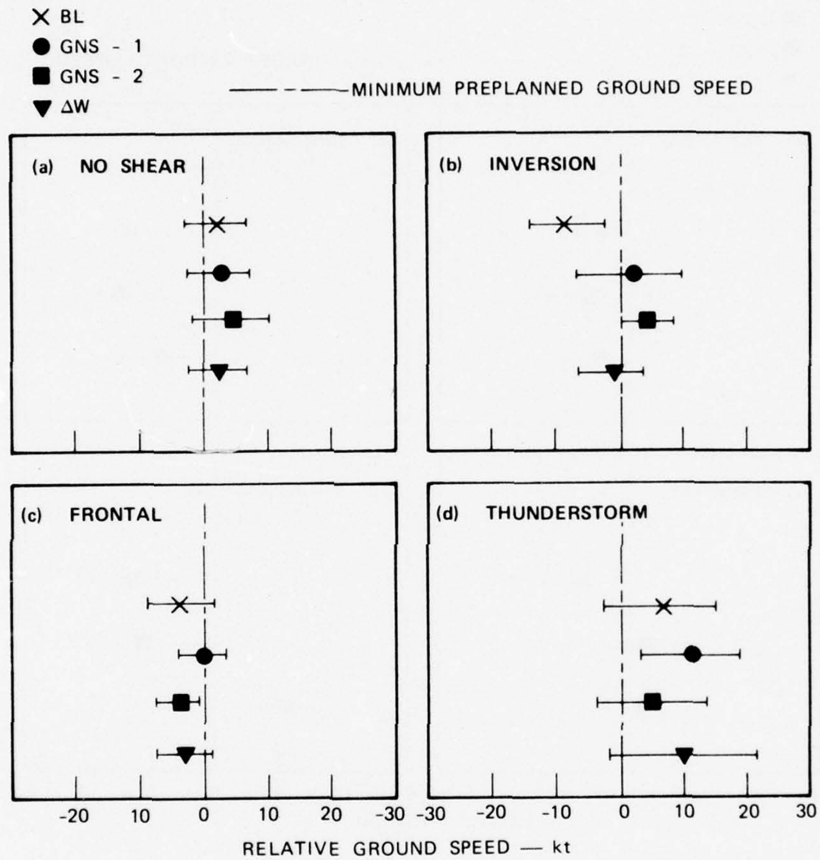


FIGURE 22 DIFFERENCE BETWEEN GROUND SPEED AND MINIMUM PREPLANNED GROUND SPEED AT TOUCHDOWN

3. Flight Path Control

Summary data presented in Figures 23 and 24 are included to indicate the effects of the experimental airspeed management techniques on the pilot performance of the glide path and localizer tracking task. The data points in these figures are the standard deviations of glide slope and localizer displacement in dots for the 800-to-100-foot segment, averaged over pilots and data runs for the designated aid-by-wind profile combinations. Average variability in glide slope tracking did not differ substantially from baseline for any of the test concepts, although there is some tendency toward greater variability when the ΔW technique is used. As expected, glide slope displacements were greater and variability across runs was higher on the Thunderstorm shear. This appears to be primarily an effect of the wind profile, although somewhat better tracking performance is indicated for the GNS-1 technique on this wind profile. Localizer tracking (Figure 24) was substantially the same for all aiding concept and wind-shear conditions.

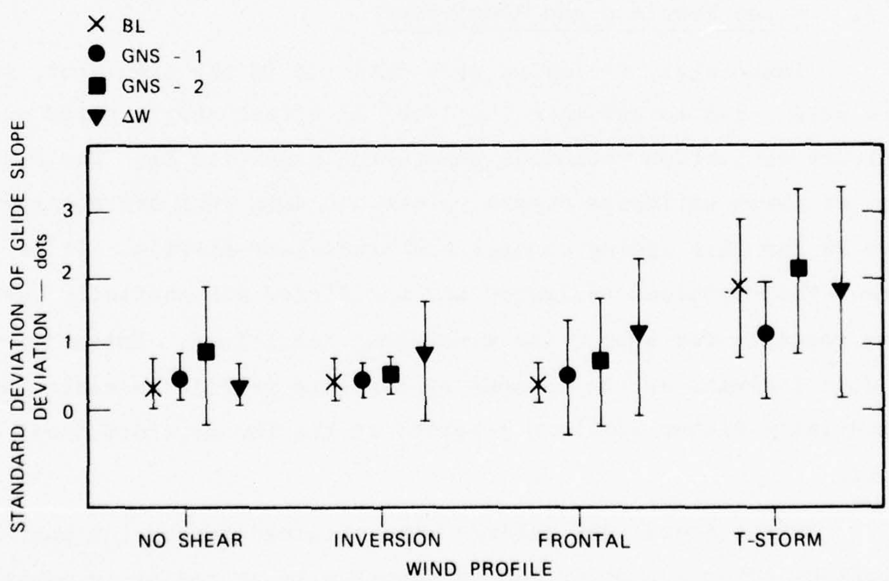


FIGURE 23 AVERAGE VARIABILITY IN GLIDE SLOPE TRACKING OVER THE 800-TO-100-FOOT APPROACH SEGMENT

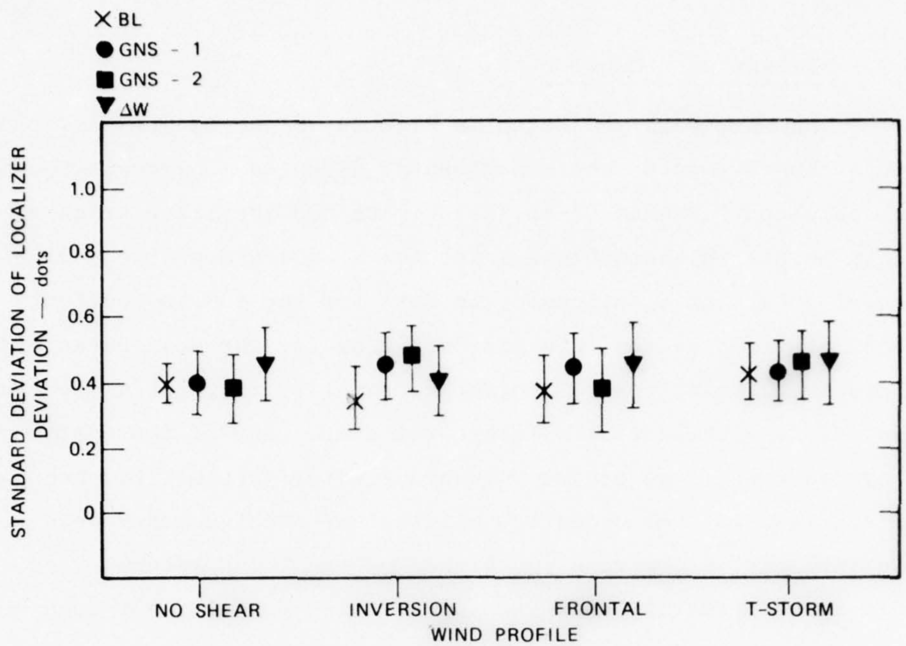


FIGURE 24 AVERAGE VARIABILITY IN LOCALIZER TRACKING OVER THE 800-TO-100-FOOT APPROACH SEGMENT

4. Pilot Workload and Acceptance

Immediately following each data run in the simulator, subject pilots were asked to estimate the level of effort they applied using the direct estimation technique described in Section II. The mean values of these estimates across pilots and data runs are plotted in Figure 25 for each aiding concept and wind-shear profile. It is apparent that workload estimates did not differ substantially across aiding concepts for any of the wind-shear conditions. Estimated work-load does increase as the demands of the wind profile increase, with substantially higher workload reported on the Thunderstorm shear en-counter.

Pilot acceptance ratings were obtained during the post-session debriefings after the pilot had an opportunity to review in detail his experience with the aiding concept used in that session. On the basis of this experience, pilots were asked to indicate, on a five-point rating

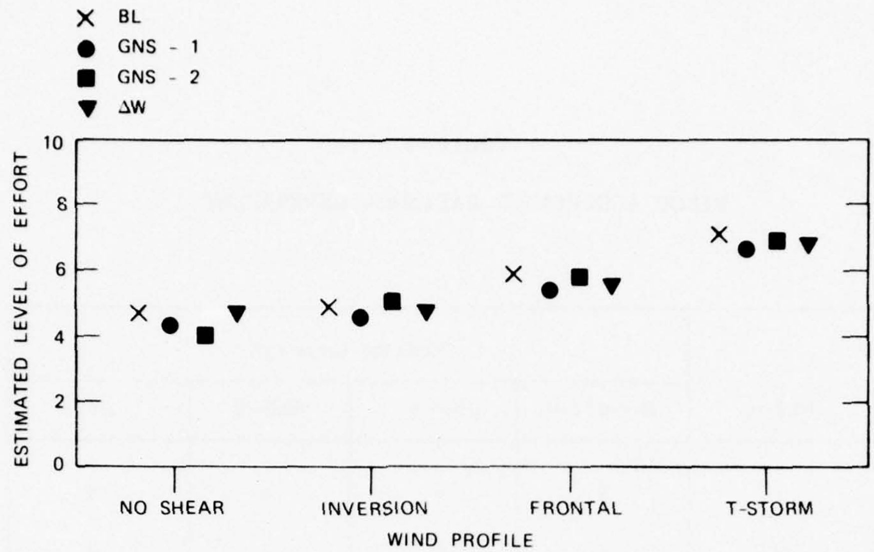


FIGURE 25 MEAN PILOT WORKLOAD RATINGS, EXPERIMENT 1

scale, the level of confidence they would have in their ability to cope with actual wind shears of the kind represented in the simulation using the designated aid.

Ratings provided by each pilot are listed in Table 4 for each aiding concept. Consistently higher ratings were obtained for the ground speed techniques, with the GNS-1 display rated highest. Acceptance ratings for the ΔW technique were at the same level as the baseline condition.

D. Pilot Critique of the Aiding Concepts

Subject pilot assessments of the effectiveness and operational utility of each of the alternative airspeed management techniques are summarized below. Their reactions and comments regarding the test displays and how they were briefed to use them are also noted. The material summarized is based on both the debriefing interviews and on the observations of the project pilot who was in the cab with the subjects on all training and data runs.

Table 4

PILOT ACCEPTANCE RATINGS--EXPERIMENT 1

Pilot	Aiding Concept			
	Baseline	GNS-1	GNS-2	ΔW
1	3	4	4	4
2	4	4	4	4
3	3	4	4	3
4	1	5	5	2
5	4	3	3	3
6	3	3	2	4
7	2	4	3	1
8	4	4	3	4
Mean	3	3.9	3.5	3.1

Scale: 1 Not at all confident.
2 Uncertain.
3 Somewhat confident.
4 Confident.
5 Highly confident.

1. Ground Speed Pointer

In general, use of ground speed information and the "minimum preplanned ground speed" technique required considerable briefing if the pilots had not had some prior contact with it. Most pilots seemed to agree that this presentation was clearly the best and most graphic presentation of the type of shear they were encountering. The spread between the two pointers provided an easily read picture of tail wind or head wind and its amount. Also, the spread between the pointers and their rate of spread or closure helped to detect the amount of shear. Some objected to "cluttering" the airspeed indicator with another pointer, and some confusion was expressed as to which pointer they should be flying, especially when both of them were active. This confusion was felt to be partially due to the newness of the concept.

Seven of the eight pilots felt that this technique would be an effective way to deal with low-level shear, and all of them said it would be practical for routine airline operations. Difficulties with the addition of a second pointer and reference bug on the airspeed indicator were expressed by all of the pilots, and one felt that the potential for confusion between the pointers at low altitudes, in a dynamic shear environment, could be dangerous.

2. Digital Readout of Ground Speed

The pilots who objected to two pointers of the airspeed indicator liked this display better. Less confusion was noted in using the proper technique to maintain the ground speed although a few said the need to glance down below the airspeed indicator to check ground speed interfered with the normal scan pattern. Consideration of better locations for the readout, perhaps some place on the face of the airspeed indicator or closer to the attitude director indicator (ADI), were suggested. In general, the impression was that the simpler digital presentation was easier to read accurately but failed to portray the wind-shear condition as clearly and graphically as the two-pointer display.

Most of the pilots felt that the digital readout would be effective and practical for line operations but tended to express more reservations about its use than for the two-pointer display. The principal difficulty they experienced with the digital readout was its location outside the "T" scan pattern; some of the pilots felt that the additional time required to monitor the readout in this location degraded their ability to track the flight-director steering commands. Two pilots expressed strong objection to the use of red numerals on this display, suggesting that red be reserved for warning indicators.

3. Wind Difference Displays

The observer pilot felt that the subject pilots grasped the ΔW technique quickly and seemed to fly it well, consistent with their general proficiency. Most pilots liked the simplicity of the airspeed command concept, but professed a dislike in having to follow a moving reference bug. Most pilots confessed that they were too occupied with the task of matching their speed with the command bug to derive much information from the digital readout. Some said they just forgot the digital readout entirely because of their concentration on the changing command speed bug. All pilots questioned seemed to accept the information given by the command speed bug as being valid and some found the digital readout to be superfluous. Most pilots stated that when they did attempt to use the digital readout, they had time for only a brief glance and the only information it provided was a prediction of a gain or loss in airspeed. They did not have time to compare ΔW with the reported surface wind and attempt to determine the type of shear they were encountering.

Only two of the eight pilots felt that the ΔW technique would be effective, but most of them thought it could be helpful and practical for line operations. Some recognized the need for greater familiarity with the concept and more practice in its use, and felt that this might make their evaluation more positive. The only pilot who felt comfort-

able with the digital readout and thought it was of significant value was one with previous experience with the technique, both in the Phase 1 study and in the simulation study at NASA Ames.

4. General Comments

The three aiding concepts tested in this experiment were intended to improve pilot management of airspeed during the shear encounter. The basic idea was to enable the pilot to maintain sufficient airspeed to fly through the shear and arrive at the threshold with a safe indicated airspeed. All three concepts presented a challenging approach technique because the speed the pilot was required to maintain was subject to considerable change as the aircraft proceeded through the shear.

When the wind difference technique was used, the command airspeed bug became quite active as the negative wind difference varied during the approach, sometimes calling for changes as great as 30 to 40 knots, and substantial thrust changes were required to remain on speed. This produced a tendency to depart from the glide slope and the approach became somewhat unstable as the pilot searched for the thrust necessary to keep his speed on target. A similar tendency occurred in the use of the reference ground speed technique. As ground speed varied, the pilot had to vary thrust in order to maintain his minimum ground speed reference.

Since airline training extols over and over the merits of a stabilized approach from the outer marker to the threshold, pilots were not used to, nor comfortable with, these instabilities. Most pilots seemed to be working at capacity to maintain speed and glide slope during the approaches through the more active shears. Successful penetration of the thunderstorm shear required the pilot to make rapid and frequent control inputs and to establish high pitch attitudes and thrust levels at the low end of the approach. This is not a technique that airline passengers are likely to appreciate or accept. Another problem associated with the variable speed approaches was the tendency

to maintain the high speeds too long and cross the threshold very fast. This tendency could lead to a new problem of overshooting the runway.

The subject pilots recognized that an approach through the more severe shears represented in this study would be inherently unstable and that conventional approach management techniques could result in substantial airspeed and thrust instabilities. They generally appreciated the need for some sort of airspeed pad as insurance against substantial airspeed loss. However, some of the pilots felt that if the magnitude of the shear could be anticipated early in the approach, a safe airspeed margin could be established and maintained without chasing real-time changes in speeds due to wind effects. They felt that this would help to stabilize the approach and make the glide path tracking task easier.

E. Conclusions

The principal conclusions supported by the data obtained in this experiment are the following:

(1) Conventional approach management techniques, based on attempts to maintain a stabilized indicated airspeed from glide slope capture to the flare, were not effective in coping with the more severe Frontal and Thunderstorm windshear encounters; the percentage of within-limits approach outcomes under this condition was generally less than 50%.

(2) The analog pointer ground speed display and pilot use of the minimum preplanned ground speed technique provided substantial improvement in pilot ability to detect and successfully penetrate these more severe low-level wind shears.

(3) The manner in which ground speed information is displayed to the pilot is an important factor in achieving this improved performance and needs additional study.

(4) Pilot ability to manage the shears was not substantially better than baseline when either the digital ground speed readout or the wind difference technique was used, and in some instances performance was substantially worse.

(5) Pilot workload, reflected by pilot judgments of the level of mental and physical effort involved in managing the wind-shear encounter, was not significantly increased over baseline when any of the aiding concepts were used; substantial increases in workload are associated with the more severe Frontal and Thunderstorm shears for all aiding concepts.

(6) Pilot acceptance of the alternative airspeed management techniques for routine line operations was generally high with a clear preference for the two-pointer ground speed display.

(7) With sufficient training and familiarization, pilots will readily accept an approach management technique calling for deliberate variation in command airspeed in order to effectively cope with the low-level shear environment.

IV EXPERIMENT 2: EVALUATION OF FLIGHT PATH ANGLE DISPLAY*

A. Review and Analysis

The second experiment in Phase 2 evaluations of pilot aiding concepts for the low-level wind-shear encounter was concerned with the potential contribution of a panel display of flight path angle (FPA). Phase 1 testing of this aiding concept was considered inconclusive because clear guidelines for pilot interpretation and use of the information in the conduct of the approach had not been developed.

For the Phase 2 presentation of FPA, Dr. A. C. McTee (BR) arranged the loan by the USAF Flight Dynamics Laboratory of a Lear-Siegler 4058AK flight director unit, which incorporates a moving tape display of FPA integrated with the Attitude Director Indicator (ADI), shown in Figure 26. This display provides the pilot with a clear indication of FPA, in degrees, within his primary instrument scan pattern. This display corrected the deficiencies in display location and readability; however, it should be noted that the display unit was selected on the basis of availability and that it has not been designed to support any particular approach-management concept.

In order to establish a basis for the development of pilot use concepts for Phase 2 testing, a survey was conducted of actual pilot use of head-down displays of FPA for aircraft control during approach and landing. The USAF Flight Dynamics Laboratory, Wright-Patterson AFB, was known to have designed and fabricated a number of head-down displays of FPA that had been flown since 1962 in a variety of USAF aircraft (TH-1, T-29, T-38, T-39, C-131, and C-135), in simulators and in a simulated RPV (remotely piloted vehicle) ground controller's station. As a first step toward tapping this well of experience, a short questionnaire (Appendix D) was prepared and circulated to approximately 20 pilots

*This section was written by Mr. Michael G. Keenan.

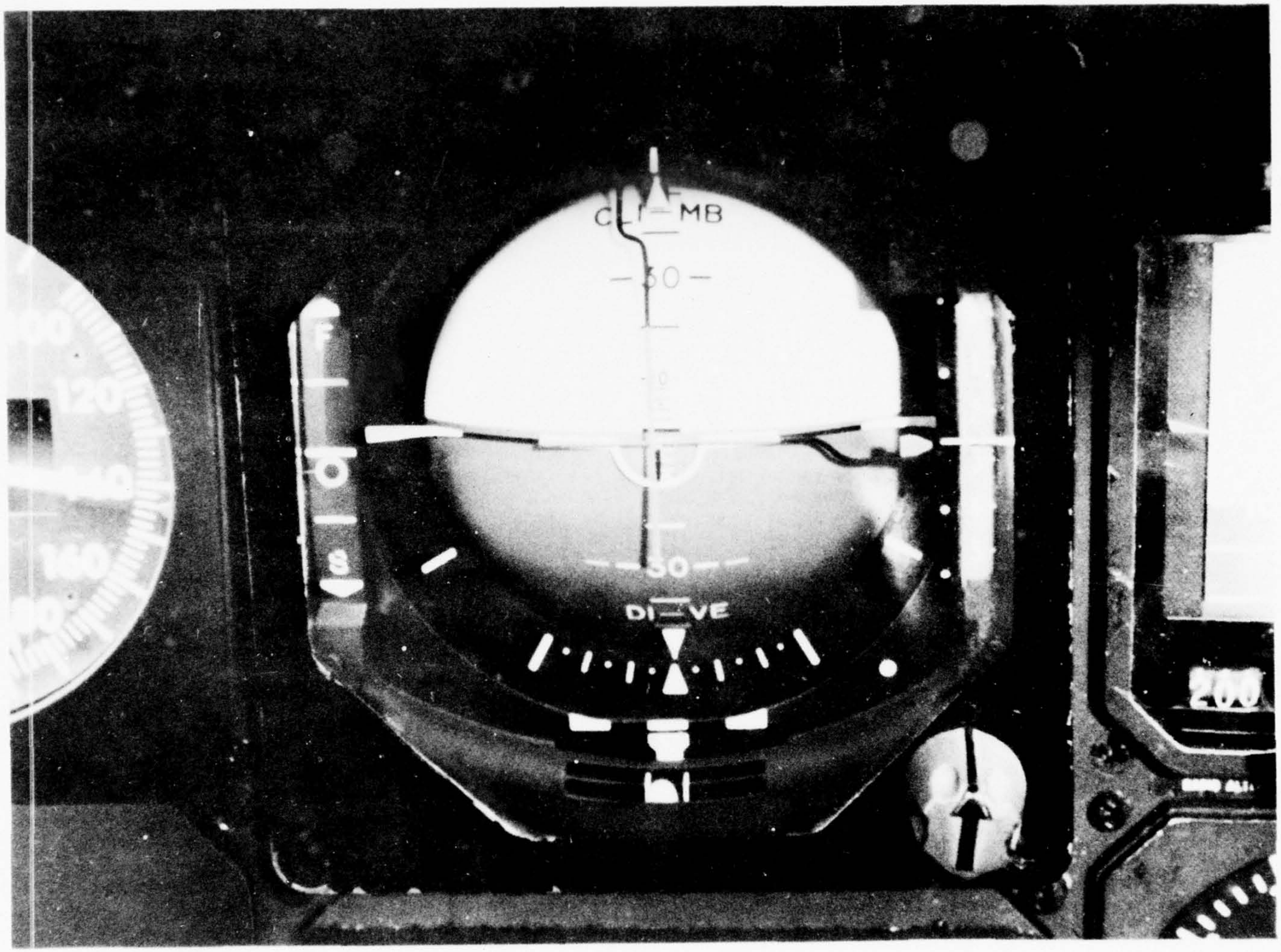


FIGURE 26 LEAR SIEGLER FLIGHT DIRECTOR WITH FPA SCALE

who could be identified as having flown one or more of these USAF aircraft. Additionally, a meeting was convened at Wright-Patterson AFB, Ohio to discuss FPA usage with some of these pilots, and with the engineering and supervisory personnel who had participated in the FPA testing.

It was clear from the results of the questionnaire and meeting that the USAF experience and testing had not really examined the application of FPA to wind shear. Some pilots reported having encountered shears while flying FPA, but, as one pilot said, "shears could only be detected by relating FPA to a ground-referenced angle such as glide slope."

The FPA algorithms that were discussed were:

(1) $\dot{h} \div IAS$
(2) Pitch angle minus angle of attack
(3) $(\dot{h} + \ddot{h}) \div IAS$
(4) $\dot{h} \div (IAS + \ddot{x})$
(5) $(\dot{h} + \ddot{h}) \div (IAS + \ddot{x})$
(6) $\dot{h} \div \dot{x}$

where

$\dot{h}$ = Vertical velocity (e.g., barometric)

IAS = Indicated airspeed

$\ddot{h}$ = Vertical acceleration (e.g. as measured by a normal accelerometer)

$\dot{x}$ = Longitudinal velocity

$\ddot{x}$ = Longitudinal acceleration.

Types 1, 2, and 3 had been instrumented and flown; the others were speculative. The most likely candidate was judged to be 3, which involves acceleration-quickened vertical velocity and airspeed measurement in the longitudinal term. The time constant used for smoothing was not specified; however, pilot comments again indicated that the USAF work

had never been able to find a time constant appropriate both to control in the short term and to performance monitoring in the long term.

The results of the literature review, questionnaire, and meeting showed that the formulation and usage of FPA were exceedingly complex. Seven potential formulations of FPA were identified, and the pilots who had flown the USAF aircraft reported having used FPA in a variety of ways not directly related to wind shear. They had used FPA as a tape display, as a pitch steering command based on FPA error, and in various mixes with glide slope deviation.

In an attempt to clarify this issue, a computer simulation study of alternative FPA based control laws was carried out at SRI. The computer was programmed with a set of simplified longitudinal equations for DC-10 aerodynamics, and various forms of FPA were inserted into the pitch and throttle control loops for testing against simulated wind shears. The results identified two potentially effective ways of using FPA as a glide path control parameter, and a set of use concepts was developed along these lines. This study is documented in Appendix E.

Preliminary to Experiment 2, it was felt that these use concepts should be validated in the simulator. Accordingly, a consultant, Don Condra, an ex-USAF pilot with considerable flight experience using FPA displays, was asked to evaluate the use concepts. After several hours simulator flying, both pilot-consultant and the project pilot decided that the use concepts were not effective with the FPA algorithms and time constants currently mechanized. The display was too active in rough air and during the shears to provide effective control information. Therefore, the use concepts were revised to suggest the FPA display be used in a monitoring context, and these were the use concepts briefed during the study.

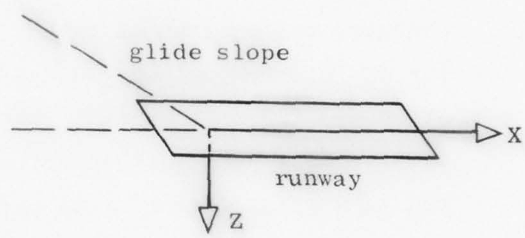
B. Description of FPA Aiding Concepts Testing

1. Flight Path Angle Display

Flight path angle was presented on a moving tape display located just to the right of the ADI and integrated into the ADI instrumentation package (Figure 26), providing a direct reading in degrees, and color coded to match the ADI presentation.

Two ways of computing FPA were chosen for driving the test display. The first was referred to as "ground-referenced" FPA (designated as γ_{GM}), and was defined as a ratio of vertical speed to ground speed:

$$\gamma_{GM} = \frac{V_{HM}}{V_{XM}}$$



where

$$V_{HM} = \frac{-1}{1 + \tau_H s} \dot{Z}$$

$$V_{XM} = \frac{1}{1 + \tau_X s} \dot{X}$$

with

s = Laplace transform variable

$\dot{Z}$ = Rate of change of height above runway

τ_H = 2 seconds

$\dot{X}$ = Ground speed along runway

τ_X = 5 seconds

The second method of computing FPA was intended to represent an "air-referenced" angle and was defined as a ratio of vertical speed to airspeed. This computation, as shown below, contains both ground-referenced and air-mass-referenced measurements and was therefore referred to as a hybrid (or mixed) computation of FPA and designated as γ_H.

$$\gamma_H = \frac{V_{HM}}{V_{AM}}$$

where

$$V_{HM} = \frac{-1}{1 + \tau_H s} \dot{Z}$$

$$V_{AM} = \frac{+1}{1 + \tau_A s} V_a$$

with

τ_H = 2 seconds

V_a = True airspeed

τ_A = 2 seconds

The principal difference between the two computational algo- selected for testing was that γ_H directly reflected the effects of longitudinal winds and γ_{GM} did not. The test display format was the same for both ways of computing FPA; however, the γ_H algorithm incorporated shorter time constants, and this display was expected to be more active in turbulence and more responsive to wind-shear effects than the display of γ_{GM}. The time constants for both algorithms were examined in the computer model study; the values shown were selected as being the largest that permitted the effective use of FPA in coping with the wind profiles used in this work.

2. Pilot Use Concepts

The two forms of FPA were tested in two different ways. One group of pilots flew the baseline approaches using the FPA display as a complement to the flight director for detecting and overcoming wind shear. A second group flew without pitch steering commands and used only raw glide slope data in conjunction with FPA for vertical guidance; bank steering commands were available on the flight director for lateral guidance. Pilots in both groups flew the test display as driven by

ground-referenced γ_{GM} and hybrid γ_H flight path angle computations. The ability of the pilots to manage the low-level wind-shear encounter under baseline conditions was thus contrasted with their performance on the same task using the four different FPA aiding concepts:

- γ_{GM} with flight director pitch steering commands
- γ_H with flight director pitch steering commands
- γ_{GM} without flight director pitch steering commands
- γ_H without flight director pitch steering commands

A specific control technique was associated with each of these FPA aiding concepts; however, the general manner in which FPA was used has elements common to all four aiding concepts. The general way pilots were briefed to use FPA is as follows:

(1) At the outer marker, use the FPA indication as a first cut at establishing the glide path--i.e., pitch down to achieve a -3 degree indication on the FPA tape, then adjust the rate of descent and pitch by reference to pitch steering commands and/or raw data to maintain glide slope.

(2) Monitor the FPA during approach, together with normal cross-check of pitch, vertical speed, and airspeed. FPA will offer lead information for departures from glide slope, and for returns to glide slope whenever the aircraft is displaced.

(3) FPA may also be used to estimate rate of return to, or departure from, glide slope. When above glide slope, an FPA steeper than -3 degree is needed to recapture; below glide slope, an FPA shallower than -3 degree is necessary to regain glide slope. At -3 degree FPA in a no-wind condition, the aircraft is either on the glide slope or paralleling it.

(4) In normal circumstances, FPA and pitch will change together. In approach configuration 1 degree of pitch will give approximately 1 degree of FPA change. In a wind shear, you will probably see a disruption of this pitch/FPA relationship as a first sign of the shear. This will occur in updrafts or downdrafts as well as in longitudinal winds. The pilot should be alert to these situations and take appropriate action.

(5) Small deviations in flight path angle should not require immediate action or concern. Large deviations should be corrected rapidly but smoothly by coordinated application of pitch and power.

In pre-session briefings, the general FPA use concept was modified to fit the particular aiding concept used, as follows:

(1) When the aiding concepts that called for FPA to be used with flight director pitch steering commands were flown, it was anticipated that the steering commands might conflict with the indications provided by the FPA and other cockpit displays on some wind profiles. For this situation, pilots were briefed to override the flight director and to apply the necessary pitch and power corrections as determined from the FPA display.

(2) When the γ_H computation was used, the pilots were briefed on the effects of longitudinal wind on γ_H--i.e., with the aircraft tracking the glide slope, a head wind causes a shallower reading of γ_H, and a tail wind causes a steeper reading of γ_H. The wind effects on γ_H thus make it difficult to use for estimating rate of return to, or departure from, glide slope, since it may be possible to remain on the glide slope with γ_H of 2.8 degrees in a head wind, or 3.2 degrees in a tail wind. For this reason, item 3 of the General FPA Use Concept was deemphasized for γ_H. The pilots were also told that when the display was driven by γ_H it would generally be more active than when driven by γ_{GM}.

C. Experimental Design

1. Subject Pilots

Ten pilots participated as subjects in this experiment and half of them (two airlines, two USAF, and one FAA) were the same pilots who flew the ground speed and wind difference techniques in the first experiment. The five new pilots included two airline pilots who had participated in Phase 1 testing, two airline pilots who were new to the program, and an engineering test pilot from the Lockheed Aircraft Corporation. Three of the new pilots were DC-10 qualified, averaging about 700 hours in the airplane, and one was a senior Captain with more than 22,000 flying hours.

2. Pilot Assignment to Test Conditions

Subjects were randomly assigned to two groups, with six pilots in group 1 assigned to fly the FPA/flight director combination, and four pilots in group 2 assigned to fly FPA without pitch steering information--i.e., the "raw data" condition. This arrangement was adopted in order to avoid the training problems and pilot confusion that might have resulted from having the same pilot attempt to use the two different control techniques and to switch from one technique to the other within an experimental run series. Pilots in both groups flew the assigned control techniques using both ways of computing flight path angle, but in separate sessions--i.e., using the γ_{GM} algorithm in one session and the γ_H algorithm in another.

Baseline conditions were the same as those adopted for the first experiment, and the same set of wind profiles was used. A repeated measures design was again used and called for each pilot to fly both the baseline condition and the assigned flight path angle control technique against all of the wind-shear conditions. Each pilot thus completed three 13-run sessions in the simulator: one baseline, one using the γ_{GM} display, and one using the γ_H display. Pilots used the first five runs of each session to become familiar with the assigned flight path angle control technique and then flew two runs against each of the four wind profiles for the record.

Pilot exposure to the test conditions was again partially counter-balanced to preclude any systematic bias in the data due to carry-over effects (i.e., learning, motivation, fatique, etc.). Table 5 shows the order in which pilots in the first group were assigned to baseline and test display conditions (the order was the same for both groups). Exposure to alternative wind profiles was randomized for each session in the simulator.

Table 5

ORDER OF SUBJECT PILOT ASSIGNMENT TO TEST CONDITIONS IN EXPERIMENT 2

Pilot	Run Series		
	1st	2nd	3rd
1	Baseline	γ_{GM}	γ_H
2	γ_{GM}	γ_H	Baseline
3	γ_H	Baseline	γ_{GM}
4	Baseline	γ_H	γ_{GM}
5	γ_{GM}	γ_H	Baseline
6	Baseline	γ_{GM}	γ_H

The second experiment was conducted using the same general procedures as those established for Experiment 1. Pilots were scheduled in pairs and alternated sessions in the simulator, and a similar pattern of initial briefings, individual session briefings, and debriefings was followed. The ILS approach charts, aircraft configuration, run data cards, observer pilot role, and coordination of data recording activities developed for the first experiment were also used again in this exercise.

Criterion measures for evaluating the effectiveness of the flight path angle control techniques relative to baseline performance were also basically the same. In this experiment, however, primary emphasis was placed on glide slope tracking performance over the 800-to-100-foot approach profile segment. Two new parameters were added to the run data printout to indicate the accuracy of pilot control of flight path angle during this profile segment--i.e., the mean and standard deviation of flight path angle.

D. Results and Discussion

1. Approach and Landing Outcomes

In this experiment the aiding concepts evaluated represent alternating methods of flight path control from the point of glide slope capture to flare initiation. The principal indicator of the relative effectiveness of these techniques is an overall index of approach outcomes as defined in Section III for Experiment 1. Similarly, the landing outcomes, which were also defined earlier, provide a secondary indicator of relative effectiveness. Data showing contrasts between baseline and aiding concepts are given in Figures 27 and 28. As in Experiment 1, data points in these summary plots are the proportion of within-limits approach and landing outcomes relative to the total number attempted under each designated wind profile condition. In deriving the proportion within limits at 100 feet, a missed approach initiated above 100 feet was counted as outside limits without regard to recorded flight path offsets or vertical speed at the Inner Marker. A go-around below 100 feet was counted as an out-of-limits touchdown.

Figures 27 and 28 show no substantial improvement in approach outcomes for the two flight path angle techniques as compared with baseline performance. Generally the data show a higher proportion of within-limits approaches at 100 feet for the baseline condition. When γ_{GM} with raw data was used on the Frontal shear, approach outcomes were significantly worse than baseline ($p < 0.05$).

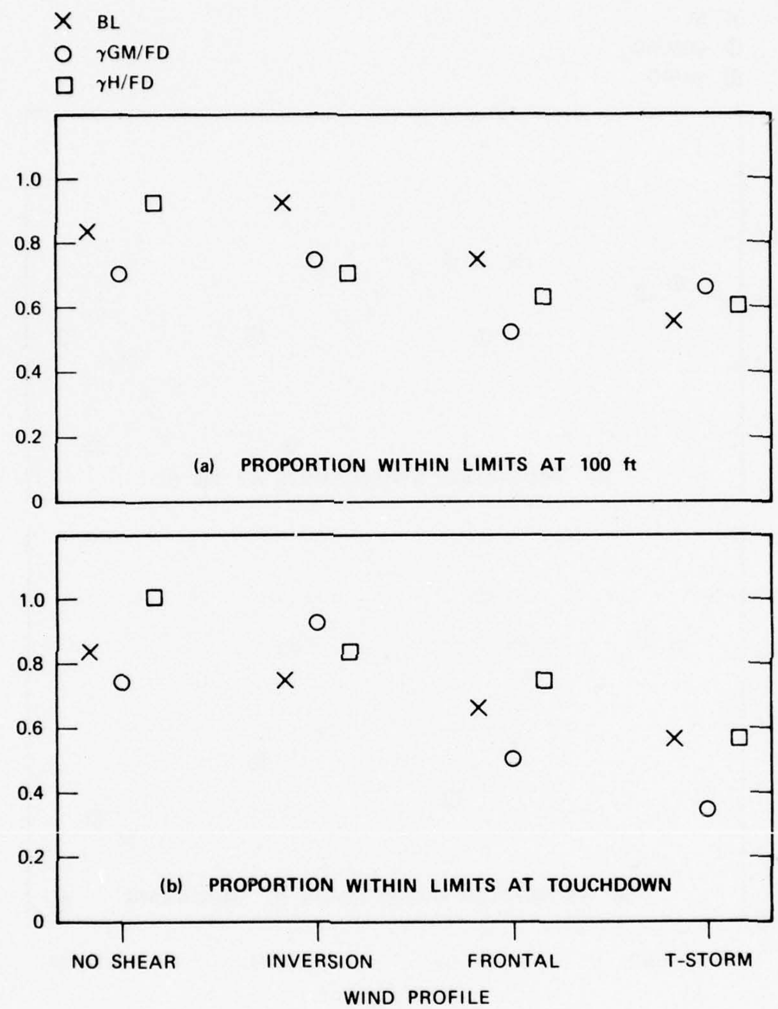


FIGURE 27 APPROACH OUTCOMES, FPA WITH FLIGHT DIRECTOR

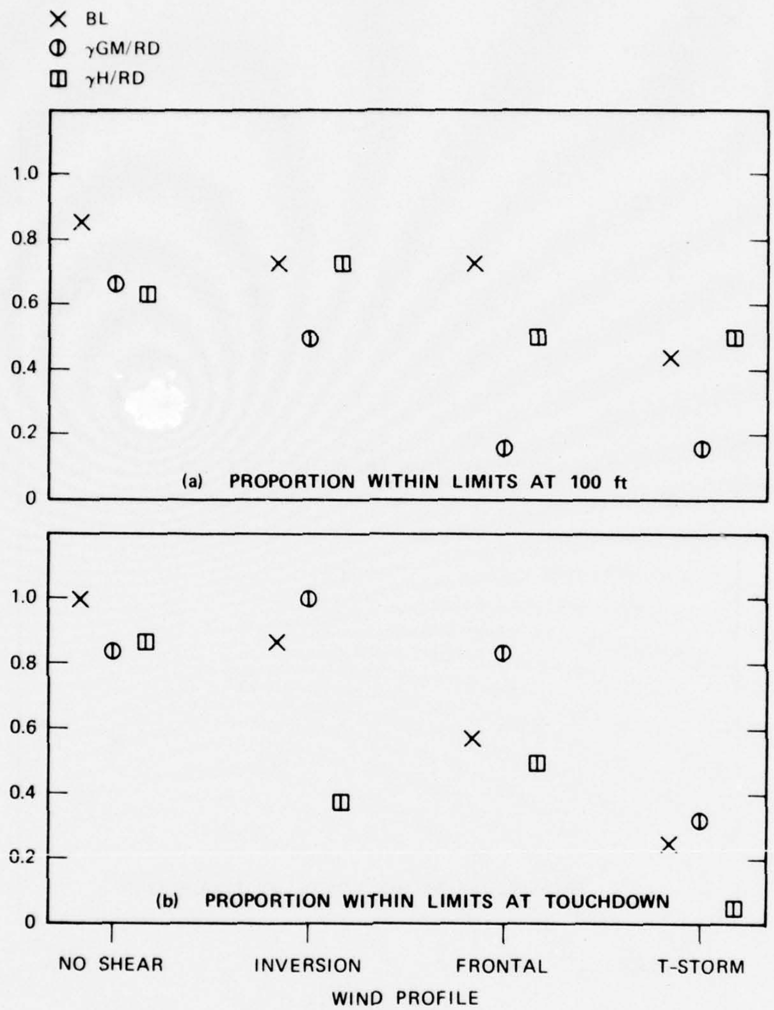


FIGURE 28 APPROACH OUTCOMES, FPA WITH RAW DATA

Landing outcomes show a greater spread over aiding concepts and wind profiles, and do not correlate well with approach outcomes. The data show some slight improvement over baseline for γ_H with flight director on the Inversion and Frontal profiles. However, these differences are not statistically significant.

No clear-cut improvement over baseline techniques in either approach outcomes or landing outcomes is evident from these data. The magnitude of the differences shown can be partly attributed to the limited size of the data set. For the tests using FPA with flight director, the maximum sample base was 12 (6 subjects x 2 runs per subject). For the tests using FPA with raw data, the maximum sample base was 8 (4 subjects x 2 runs per subject).

Summary data on components of approach and landing outcomes are presented in the next six figures. Figure 29 shows the means and standard deviations across subject pilots for vertical offset at the inner marker. Offsets were consistently smaller for baseline than for γ with flight director. Results for the tests involving γ with raw data are less consistent, probably due to the smaller number of runs, as mentioned above.

Lateral offsets at the Inner Marker are plotted in Figure 30 and 31. In most instances, mean baseline offsets are smaller and less variable than those shown for other FPA aiding concepts. This is not a surprising result, in that the aiding concepts tested were intended to assist in vertical guidance only.

Scatter plots of approach-outcome positions for Frontal and Thunderstorm profiles are given in Appendix F.

Figure 32 shows the mean and standard deviation of vertical speed at the Inner Marker. These data show that the mean vertical speed was close to the normal at 12 feet per second for all wind profiles except the Thunderstorm for all aiding concepts. The lower rates of descent shown for the Thunderstorm profile probably reflect the effects of pilot attempts to counter the downdrafts encountered just prior to

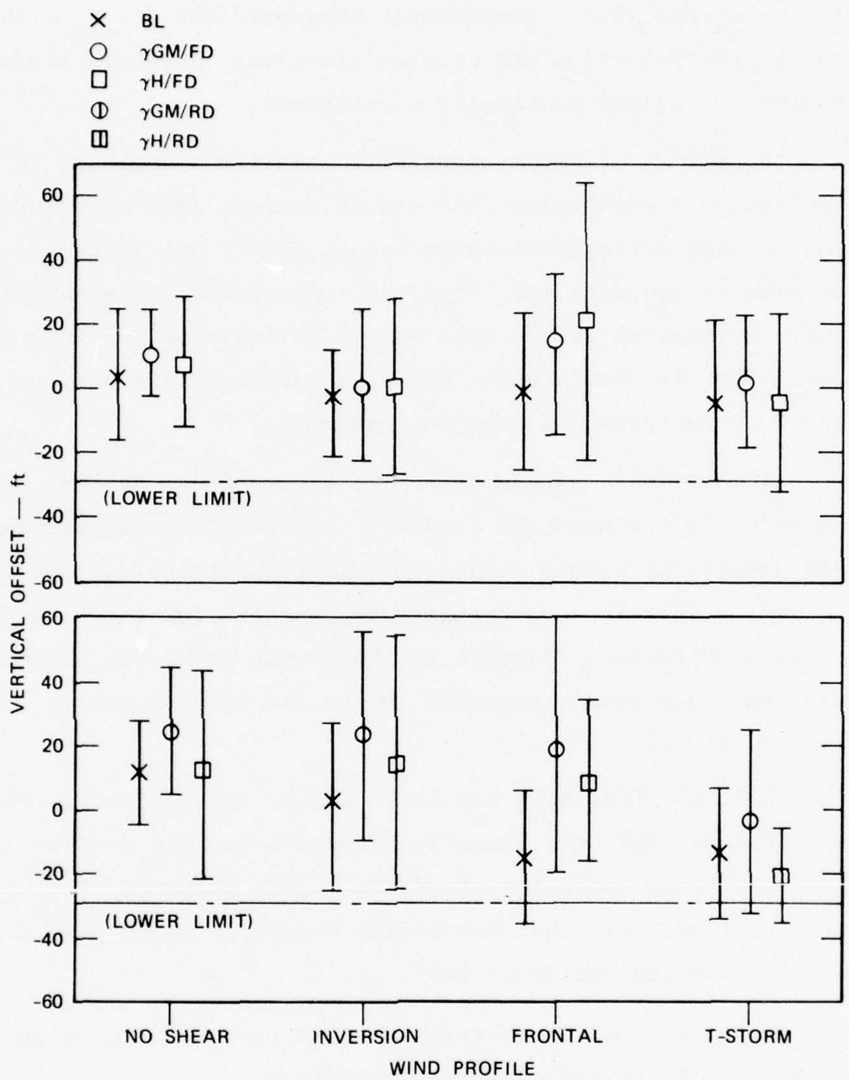


FIGURE 29 VERTICAL OFFSET AT INNER MARKER

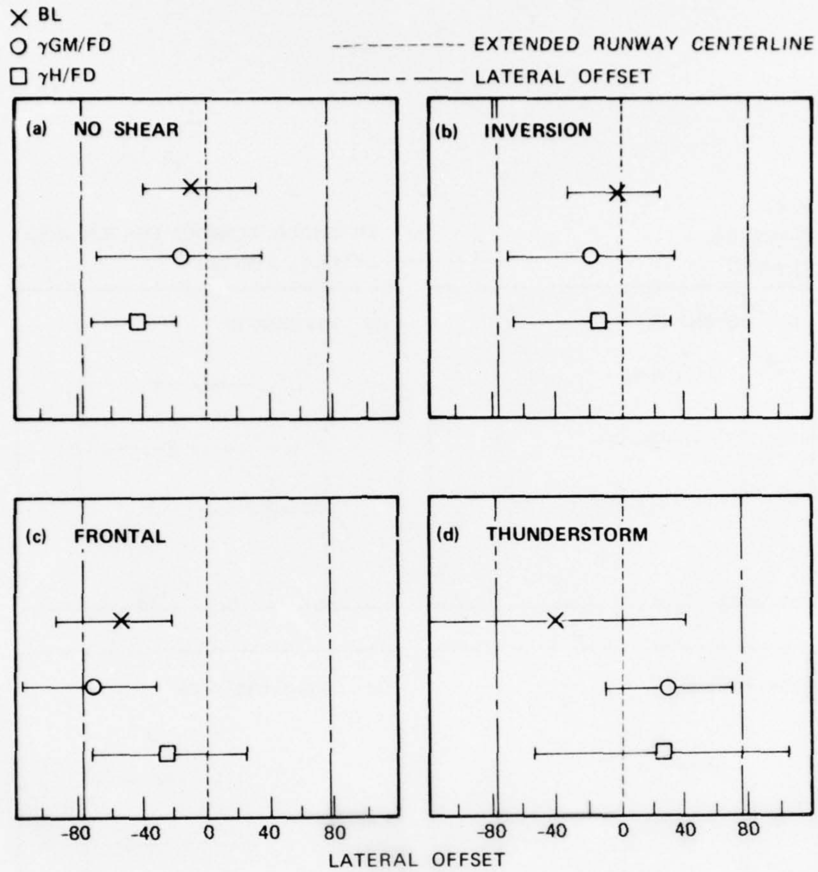


FIGURE 30 LATERAL OFFSET AT INNER MARKER, FPA WITH FLIGHT DIRECTOR

the 100-foot point with additional thrust. The data show little difference between baseline and aiding concepts in vertical speed at the Inner Marker within each wind profile.

Figures 33 and 34 show mean touchdown positions to be within longitudinal limits for all aiding concepts and wind profiles. Standard deviations about the mean also fall within limits, except for the Thunderstorm case in which one landing short of threshold occurred.

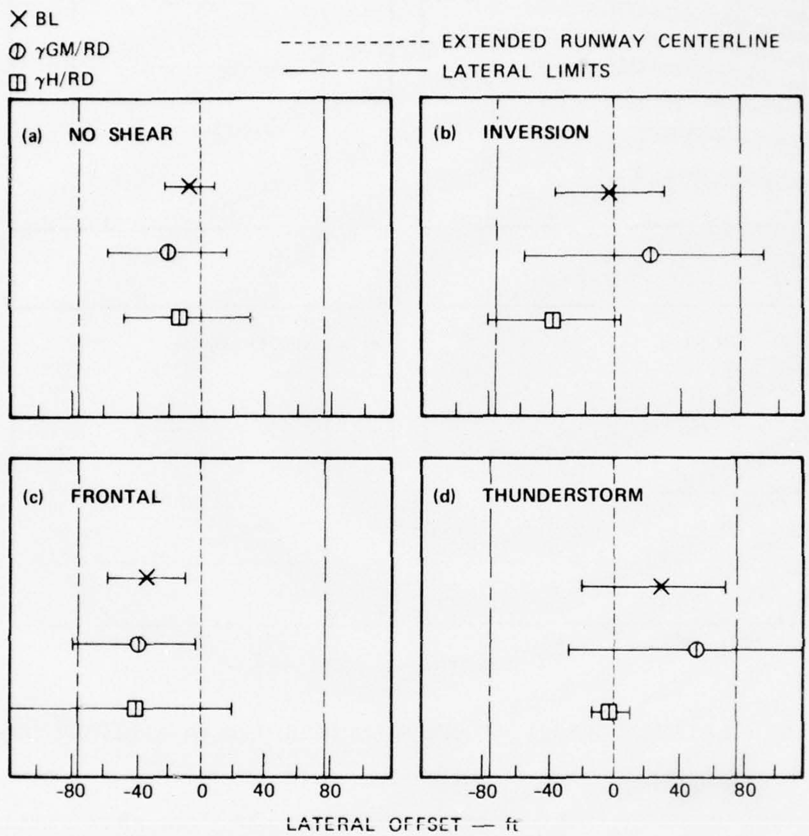


FIGURE 31 LATERAL OFFSET AT INNER MARKER, FPA WITH RAW DATA

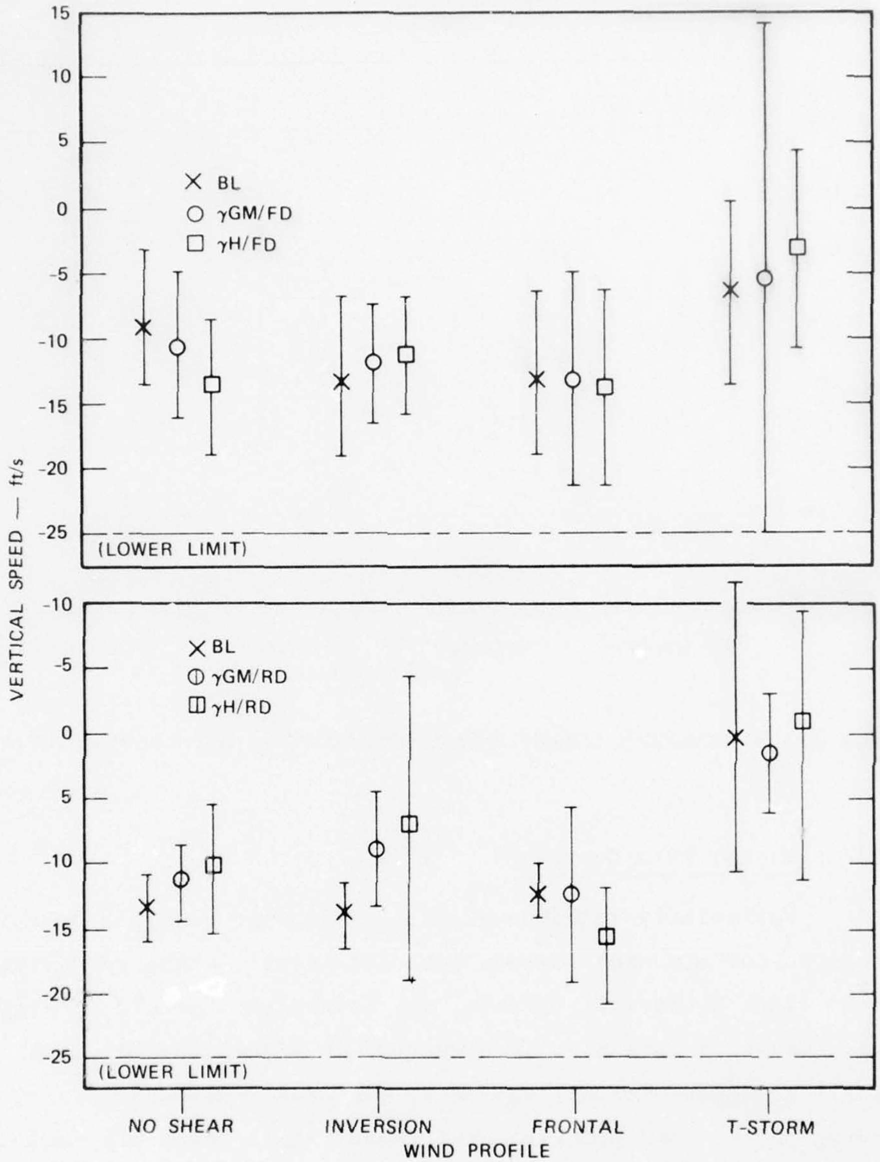


FIGURE 32 MEAN AND STANDARD DEVIATION OF VERTICAL SPEED AT THE INNER MARKER

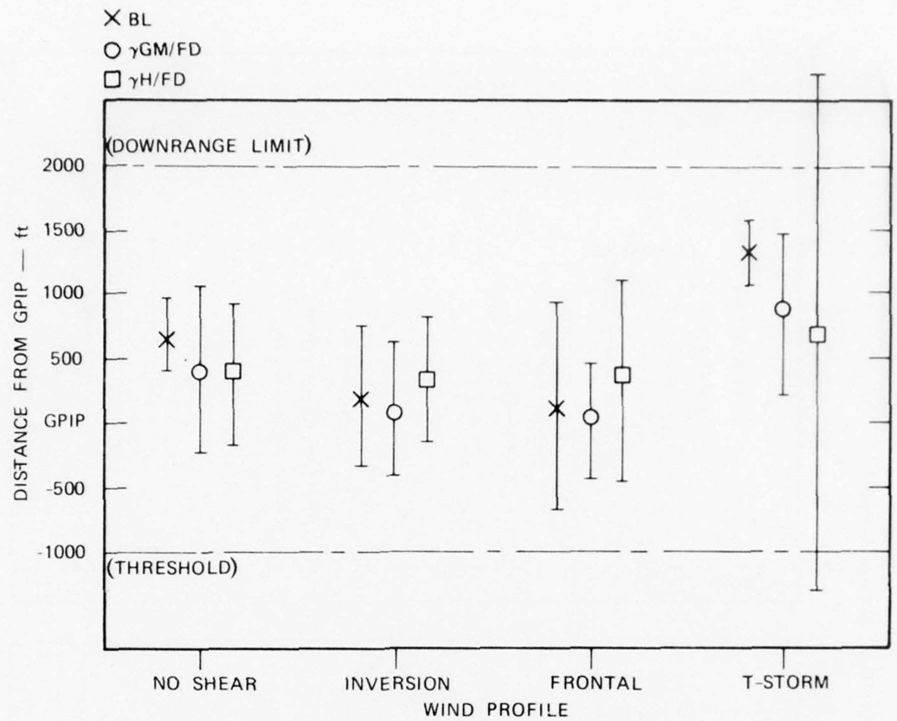


FIGURE 33 TOUCHDOWN LONGITUDINAL POSITION, FPA WITH FLIGHT DIRECTOR

2. Flight Path Control

Variability in glide slope tracking was examined over the 800-to-100-foot approach segment for each pilot. Standard deviations of glide slope deviation, in dots, were averaged over all subject pilots, and the resulting data plot is presented in Figure 35. Glide slope variability, taken over all subjects, had mean values to $\frac{1}{2}$ to $1\frac{1}{2}$ dots depending on the wind profile. The Thunderstorm generally showed higher values, underscoring the greater activity involved in glide slope tracking under that shear condition. Baseline tracking was as good or better than when aiding concepts were used across all wind profiles. In general, baseline also showed less variability across pilots, consistent with greater uniformity in subjects' familiarity with those techniques.

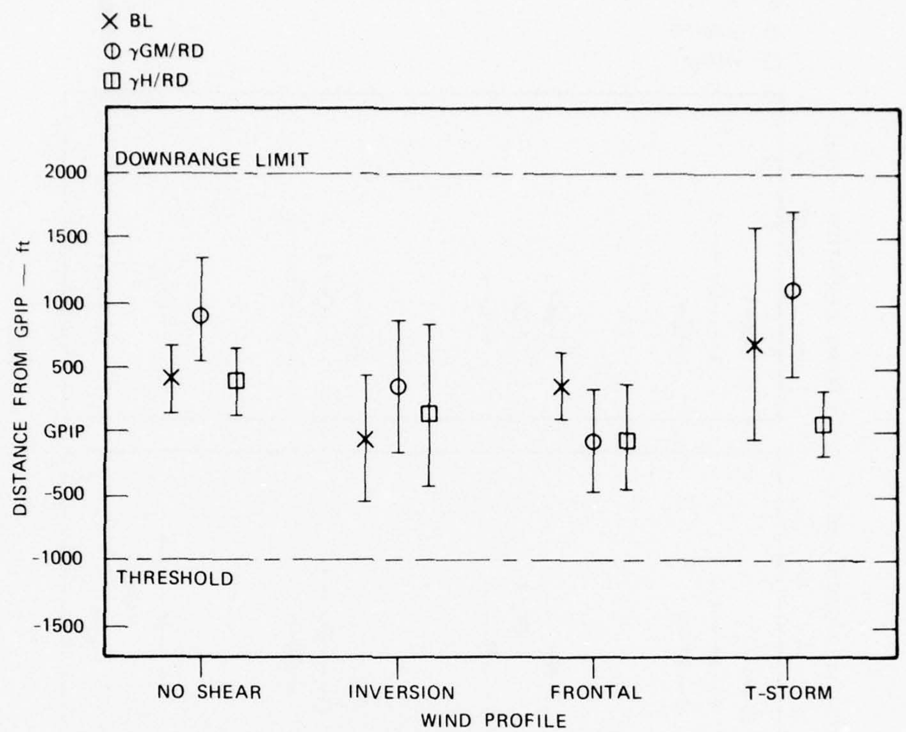


FIGURE 34 TOUCHDOWN LONGITUDINAL POSITION, FPA WITH RAW DATA

Standard deviations of localizer tracking over the 800-to-100 foot approach segment averaged over all subject pilots are plotted in Figure 36. The baseline condition shows somewhat smaller deviations for all wind profiles when averaged over the two subject groups. Variability among subject pilots was also generally smaller for baseline. Since lateral tracking was not the purpose of the aiding concepts treated in Experiment 2, these results are not surprising. It is noteworthy, however that lateral tracking performance was good (less than ½ dot) for all aiding concepts.

Figure 37 provides summary data on the maximum drop in indicated airspeed over the 800-to-100-foot approach segment. This figure shows that the maximum drop below pilot-selected target approach speeds was five knots or less for all aiding concepts on the No Shear, Inversion, and Frontal wind profiles. Much larger drops, amounting to 10 to 14 knots, were recorded for all aiding concepts on the Thunderstorm wind

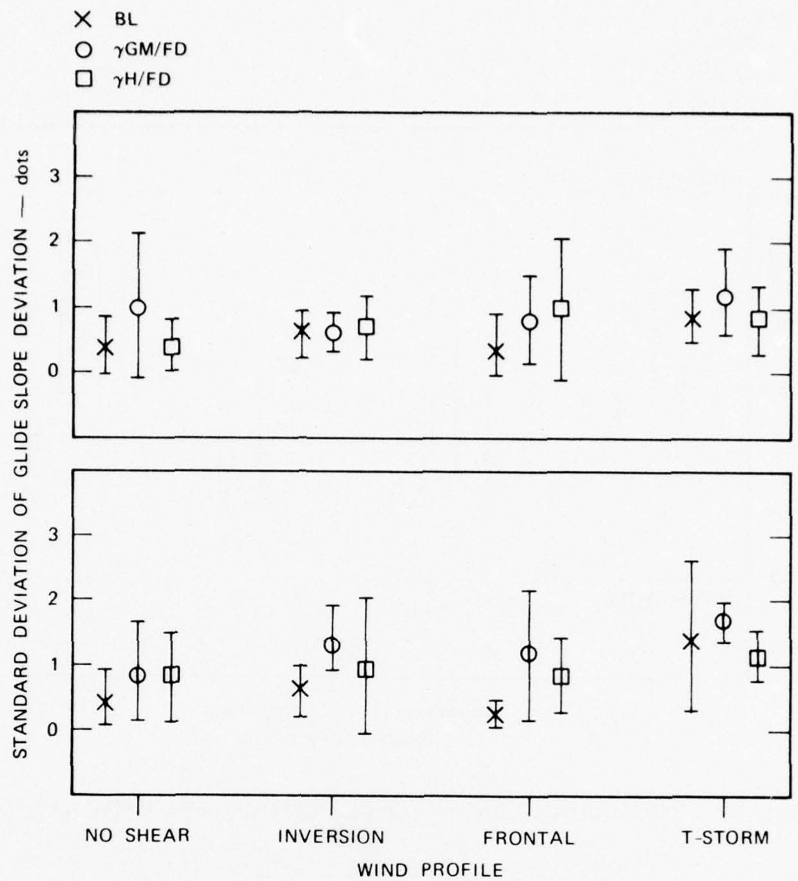


FIGURE 35 AVERAGE VARIABILITY IN GLIDE SLOPE TRACKING OVER THE 800-TO-100-FOOT APPROACH SEGMENT

profile. Mean and standard deviations across subjects showed no substantial difference between the aiding concepts and baseline. It is evident that the FPA techniques provided no significant help in minimizing airspeed drop during the shear encounters.

3. Pilot Workload and Acceptance

As in Experiment 1, subject pilots were asked to estimate their level of effort for each aiding concept, using the direct estimation technique (Section II). Figure 38 shows the results summarized across all subjects and data runs. It is apparent that workload for the FPA aiding concepts was equal to or greater than for baseline. Greatest effort was required for the Thunderstorm wind profile.

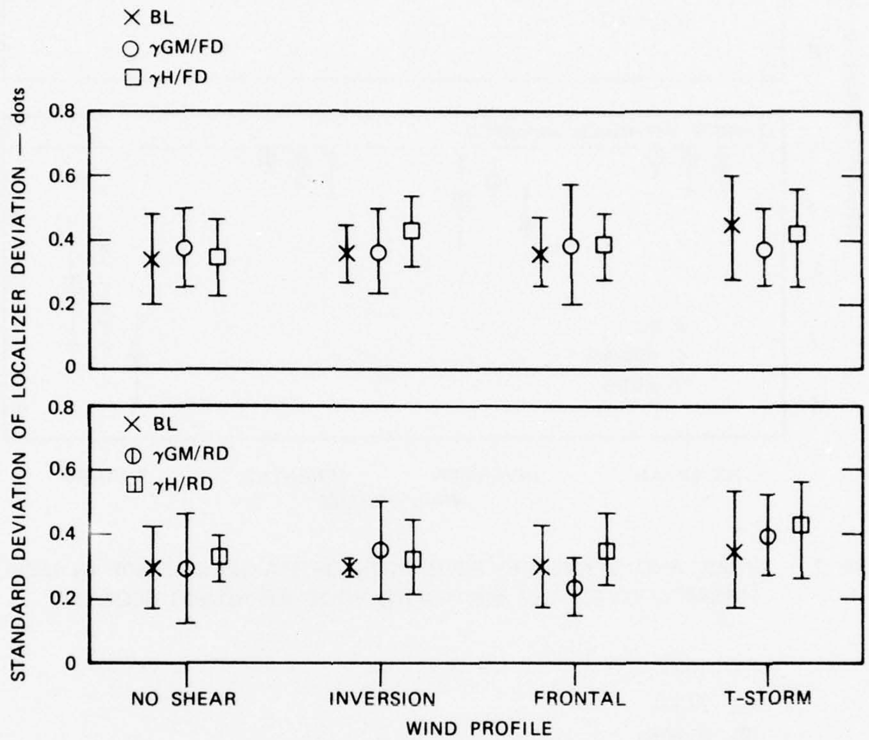


FIGURE 36 AVERAGE VARIABILITY IN LOCALIZER TRACKING OVER THE 800-TO-100-FOOT APPROACH SEGMENT

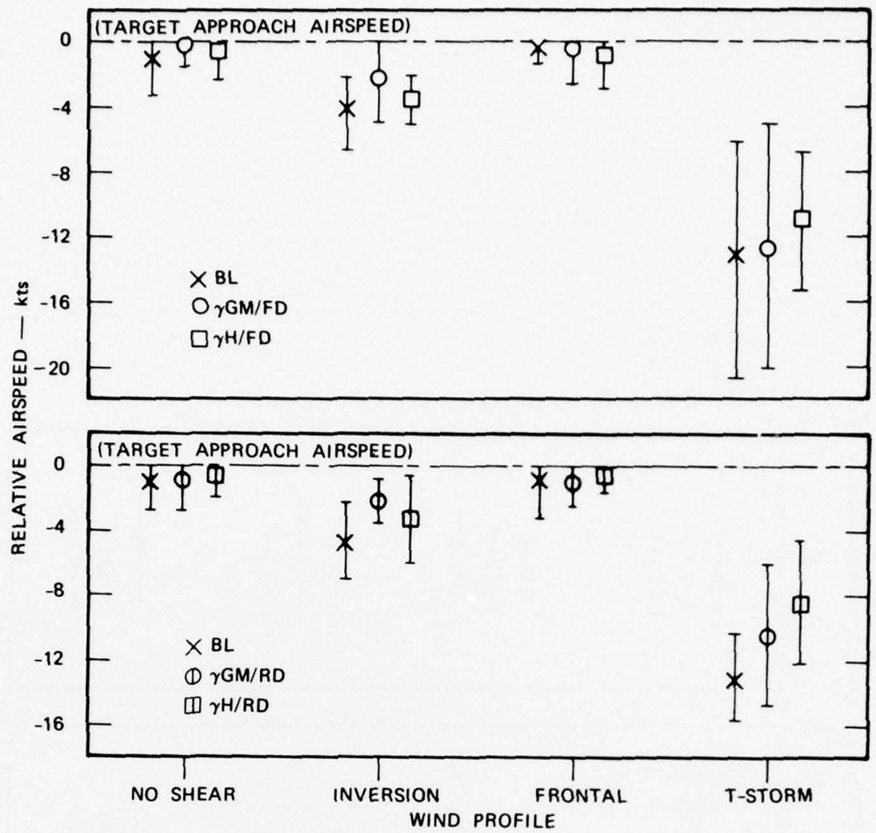


FIGURE 37 MEAN AND STANDARD DEVIATION OF MAXIMUM DROP IN INDICATED AIRSPEED OVER THE 800-TO-100-FOOT APPROACH SEGMENT

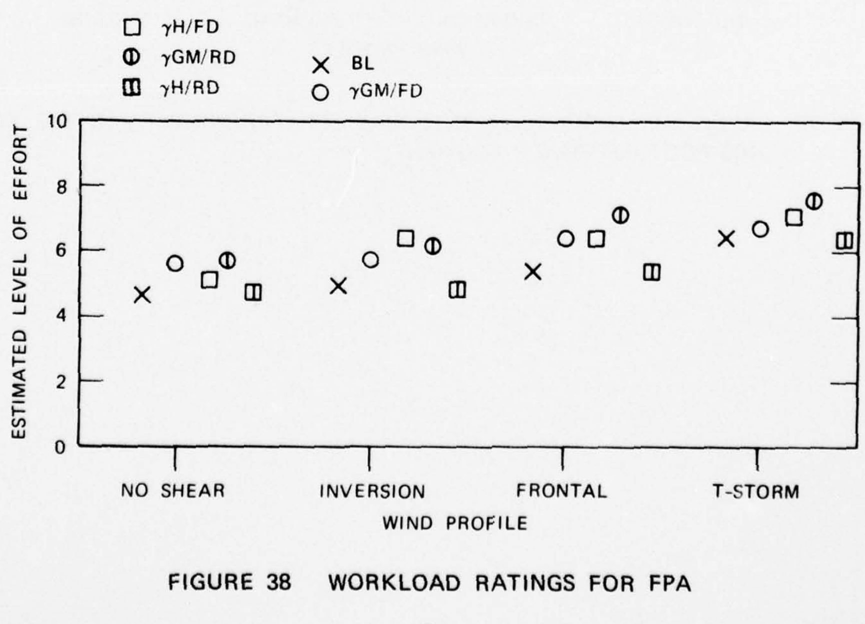


FIGURE 38 WORKLOAD RATINGS FOR FPA

Pilot acceptance ratings for the second experiment are shown in Table 6. No clear-cut preference for any of the flight path angle techniques is indicated in this polling of subject pilot acceptance. Baseline was rated considerably higher by the pilots who flew test runs involving use of flight path angle with raw data.

Table 6

PILOT ACCEPTANCE RATINGS--EXPERIMENT 2

Pilot	Baseline	$\gamma_{GM/FD}$	$\gamma_{H/FD}$	$\gamma_{GM/RD}$	$\gamma_{H/RD}$
1	3	3	--		
2	3	4	4		
5	5	4	4		
6	2	3	3		
9	3	3	2		
10	3	3	2		
Total	19	20	15		
Average	3.1	3.3	3.0		
3	4			3	2
4	4			--	4
7	4			--	1
8	4			3	3
Total	16			6	10
Average	4.0			3.0	2.5

E. Pilot Critique of the Aiding Concepts

1. FPA Displays

As mentioned earlier, both FPA algorithms were displayed to the pilot by means of the moving tape display incorporated in the Lear-Siegler 4058AK ADI (see Figure 26). The tape display was driven by either γ_{GM} or γ_{H}, depending on the particular run series.

Pilot comments related to the tape display itself were generally favorable. The location was well liked, especially so since the glide slope deviation indicator and scale were immediately adjacent

to the tape, between it and the attitude sphere. The only negative comment about the tape itself was one pilot's desire for more contrast between the tape and its imprinted numerals. The tape is presently a medium brown with white numbering. The scale factor of 1/3-inch tape movement per degree of FPA was apparently quite satisfactory.

Although the ADI itself was not a specific test item, pilot opinions of it were solicited for our information, and the following comments were received:

(1) The fuselage dot was not conspicuous enough. One subject said that when the steering bars were centered, they completely obscured the fuselage dot. The dot color also tended to blend with the background, and most pilots would have preferred it larger and of a different hue.

(2) Several comments were made regarding the pitch scale factor. The sphere of the Lear-Siegler ADI rotates only about 2/3 as far, per degree of pitch, as that of the ADI most commonly used in the DC-10. Pilots liked the idea of pitch markings every two degrees for the first 10 degrees, but commented that the markings were hard to see because of the reduced scale factor, and that a centered bank steering bar tended to obscure the scale even further.

(3) Some pilots commented that the horizon definition would have been better with more contrast. The 4058 AK ADI has a blue over brown attitude sphere, with both the blue and brown portions gradually desaturated (lightened) toward the horizon; the sphere is darkest at the zenith and the nadir, respectively. The comments seem to indicate that the darker brown might better be placed near the horizon.

2. General Comments

The flight path angles both gave an early indication of excursion from the glide path. Most pilots, after a short time with the concept, gave up trying to control with the flight path angle and used it for an early warning device. The flight path angle change was the first indication of the shear and the pilots used it as such and then reverted to normal basic instruments for control.

The principal reason for this is that the flight path angle display, as has been stated, was very active. The hybrid FPA technique (air mass algorithm) was the most active, but both computations gave very quick movements to the instrument. This activity caused the pilots to tend to overcontrol in their efforts to correct the excursions from the desired 3-degree glide slope.

The statement most often made by pilots, in debriefings on FPA run series, was, "I could see the initiation of the shear on the FPA tape, but I couldn't tell what to do about it." The tape was reported as being so active in turbulence and in the heavier shears that it was not usable for the control tasks. This comment was made for both ground-referenced and hybrid types; comments did not favor one type over the other, in general.

Pilots reported that they could see wind effects, as briefed, in the γ_H display as values different from -3 degrees, but only in that portion of the approach prior to the shear. Once the shear was encountered, it was not possible to tell whether a change in the display was an effect of the shear or of a control input. Pilot judgment appeared to be that the FPA display served to detect shears but not to cope with them.

F. Conclusions

The following conclusions are supported by the results of Experiment 2:

(1) Both ways of computing flight path angle produced a display that was too active to use as a control instrument. The hybrid type (γ_H) was considerably more active than the ground-based type (γ_{GM}) and seemed to be especially responsive and quick in turbulence and vertical gusts.

(2) Recorded data show no significant improvement in measured performance over baseline on any of the primary evaluation criteria--i.e., approach outcome, landing outcome, or flight path control.

(3) The FPA displays seemed to increase the pilot work load. Although the flight path angle scale was in the normal scan area, it was a new item to all of the pilots and diverted their attention. It would require considerable training to be used effectively other than as an early indication of leaving the glide path.

(4) Pilots would most probably prefer to use the flight path angle displays only as an early warning of the onset of a shear encounter, and to use conventional techniques for control during the encounter.

Pilot judgment appeared to be that the FPA display served to detect shears but not to cope with them.

V EXPERIMENT 3: EVALUATION OF MODIFIED FLIGHT DIRECTOR CONTROL LAWS*

Phase 1 studies of accelerometer-augmented approach couplers[9] suggest that a substantial immunity to turbulence and low-level wind-shear effects might be realized when such techniques are applied to the development of control law algorithms for automatic flight control. Similar benefits were projected for flight director systems in support of manual flight path control if accelerometer augmentation and pitch-complemented filtering were incorporated in the algorithms for generating pitch and roll steering commands. In an extension of the Phase 1 studies, an application of accelerometer augmentation to the flight director was developed by Collins Radio, and Experiment 3 in the Phase 2 series of piloted simulator studies was devoted to an evaluation of the effectiveness of this flight director modification for manual flight path control in the presence of low-level shear.

The primary objective of this experiment was to determine the level of performance attainable by qualified subject pilots when modified flight director control laws are used to provide steering commands. The wind-shear models used for this assessment were the same as those used in the first two experiments. In order to relate the results of this experiment to the earlier evaluations of airspeed management and flight path angle control, pilot performance with the modified flight director was again contrasted with baseline performance--i.e., with performance using "conventional" flight director steering commands. In the DC-10 simulator, "conventional" refers to the flight director control laws now implemented in the DC-10 flight guidance and control system. Since some form of accelerometer augmentation and pitch complemented path damping is already included in the DC-10 system, the interpretation of the contrast with baseline is somewhat confounded. However, the DC-10

---

*This section was written by Mr. Walter B. Gartner and Dr. Wade H. Foy.

system was construed as baseline in the same sense as that adopted in earlier experiments, in that it represents an existing, already certified capability.

The results of Experiment 1 indicate that the way airspeed is managed will be an important performance factor in effectively coping with wind shear. Using conventional airspeed management practices, the potential benefits of the modified flight director steering commands may be obscured. However, the development and testing of modified airspeed control (or thrust management) algorithms that are optimally combined or integrated with the steering command algorithms for performance in shear were beyond the scope of the Phase 2 test program. Therefore, the basic airspeed control technique for Experiment 3 was manual control of pilot-selected approach airspeeds by reference to the conventionally driven Fast-Slow indicator and/or airspeed command bug. This technique was used with both baseline and modified flight director conditions.

As a secondary objective, the potential effectiveness of combining the modified flight director with an alternative airspeed control technique based on wind difference (ΔW) was assessed. This technique is the same as the ΔW-based airspeed command used in Experiment 1; however, in Experiment 3 the digital readout was not used. The ΔW technique was chosen because its display was coordinated with the flight director Fast-Slow command and also because it was considered desirable to conduct a second evaluation of the ΔW technique. The comparatively poor approach outcome performance recorded for the ΔW concept in first experiment seemed to be attributable to the pilot's attempt to interpret and use the digital readout of ΔW. The disruption of their scan and the time required to assimilate the unfamiliar wind difference information degraded pilot performance of the primary flight path control task. The elimination of the digital readout in Experiment 3 provided an opportunity to test this contention.

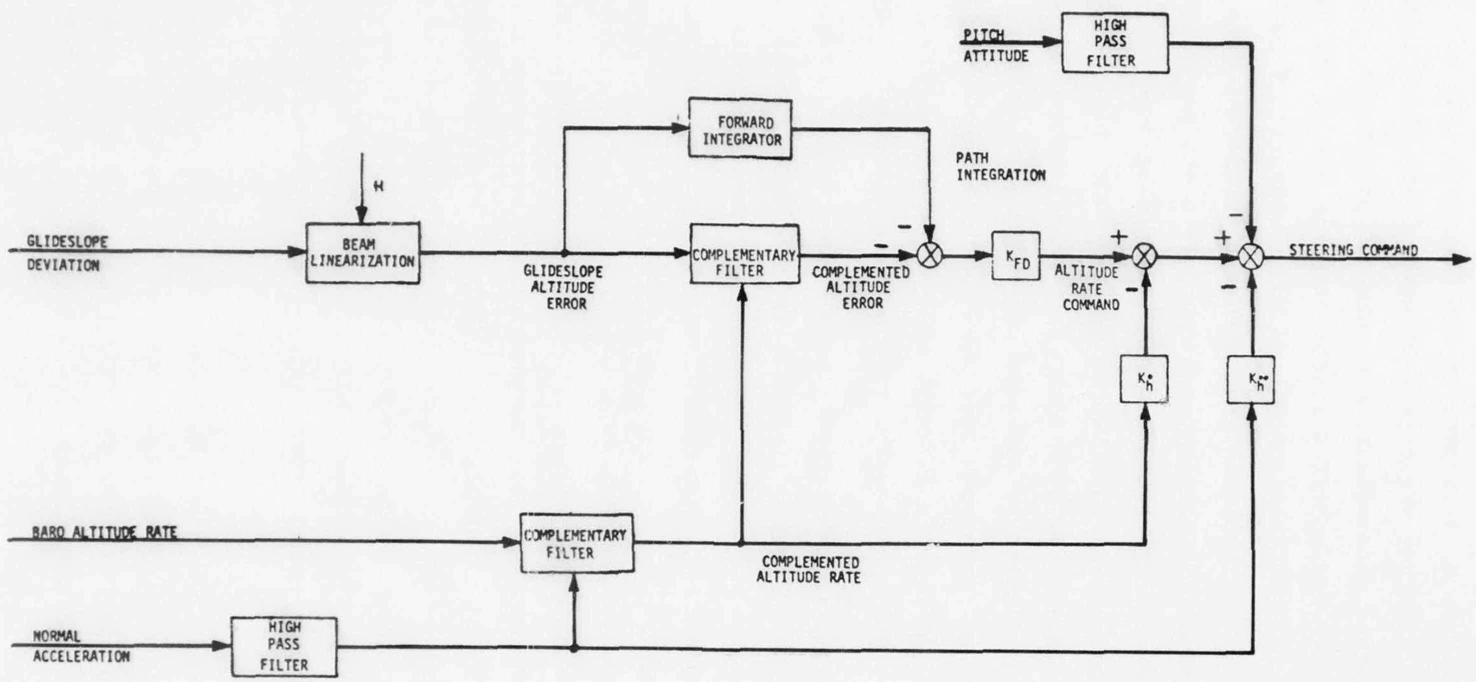
A. Description of Aiding Concepts Tested

The approach management concepts for baseline and the modified flight director were conventional. The pilot controlled the simulated aircraft

in pitch and lateral steering by reference to the flight director command bars, trying to null any displacement of the bars from center. For throttle mangement he used either the flight director "Fast-Slow" indicator or the airspeed indicator, according to his personal preference. The difference between baseline and modified flight director was in the different algorithms programmed to drive the command bars. When the Wind-Difference concept was used, the pitch and lateral steering techniques were not changed, but the throttle management was changed to the technique described in the section above on Experiment 1. The four aiding concepts tested, then, were (1) baseline, (2) modified flight director only, (3) wind difference, and (4) modified flight directo plus wind difference. The modified flight director algorithms provided for glide path tracking only; no capture mode and no flare mode were included. With each of these concepts we relied on the pilot's judgment and experience to effect coordination of pitch and lateral steering and throttle management functions.

The algorithm for computation of the modified flight director pitch steering command is illustrated in Figure 39; the basic inputs are pitch attitude angle, glide-slope deviation, altitude, normal acceleration, and rate of change of altitude. For comparison, a comparable diagram of the baseline DC-10 flight director algorithm is shown in Figure 40. Its basic inputs are pitch attitude angle, glide slope deviation, altitude, and normal acceleration. Thus, both these algorithms have acceleration augmentation. The differences are that the Collins modified signal is developed with altitude rate instead of high-pass pitch in the inner loops, complimentary filtering is used on the glide slope deviation, and the acceleration input is filtered with less smoothing. The effect of the modified algorithm is to provide a quicker steering command that response faster to wind changes (shear, gusts, turbulence) than does the baseline standard DC-10 system.

The Collins modified flight director lateral steering command is shown in block diagram form in Figure 41, and the baseline DC-10 system in Figure 42. The common inputs are roll angle, localizer deviation, and altitude. The modified system uses a lateral accelerometer input;



COLLINS RADIO-ROCKWELL INT'L
4 FEB. 1977

FAA WINDSHEAR PHASE 2
SIMPLIFIED LONGITUDINAL CONTROL LAW

FIGURE 39 SIMPLIFIED LONGITUDINAL CONTROL LAW FOR MODIFIED FLIGHT DIRECTOR

AD-A047 251 SRI INTERNATIONAL MENLO PARK CALIF F/G 1/3
PILOTED FLIGHT SIMULATOR STUDY OF LOW-LEVEL WIND SHEAR, PHASE 2--ETC(U)
MAR 77 W B GARTNER, D W ELLIS, W H FOY DOT-FA75WA-3650
UNCLASSIFIED FAA-RD-77-157 NL

2 OF 2
AD
A047251

END
DATE
FILMED
1 -78
DDC

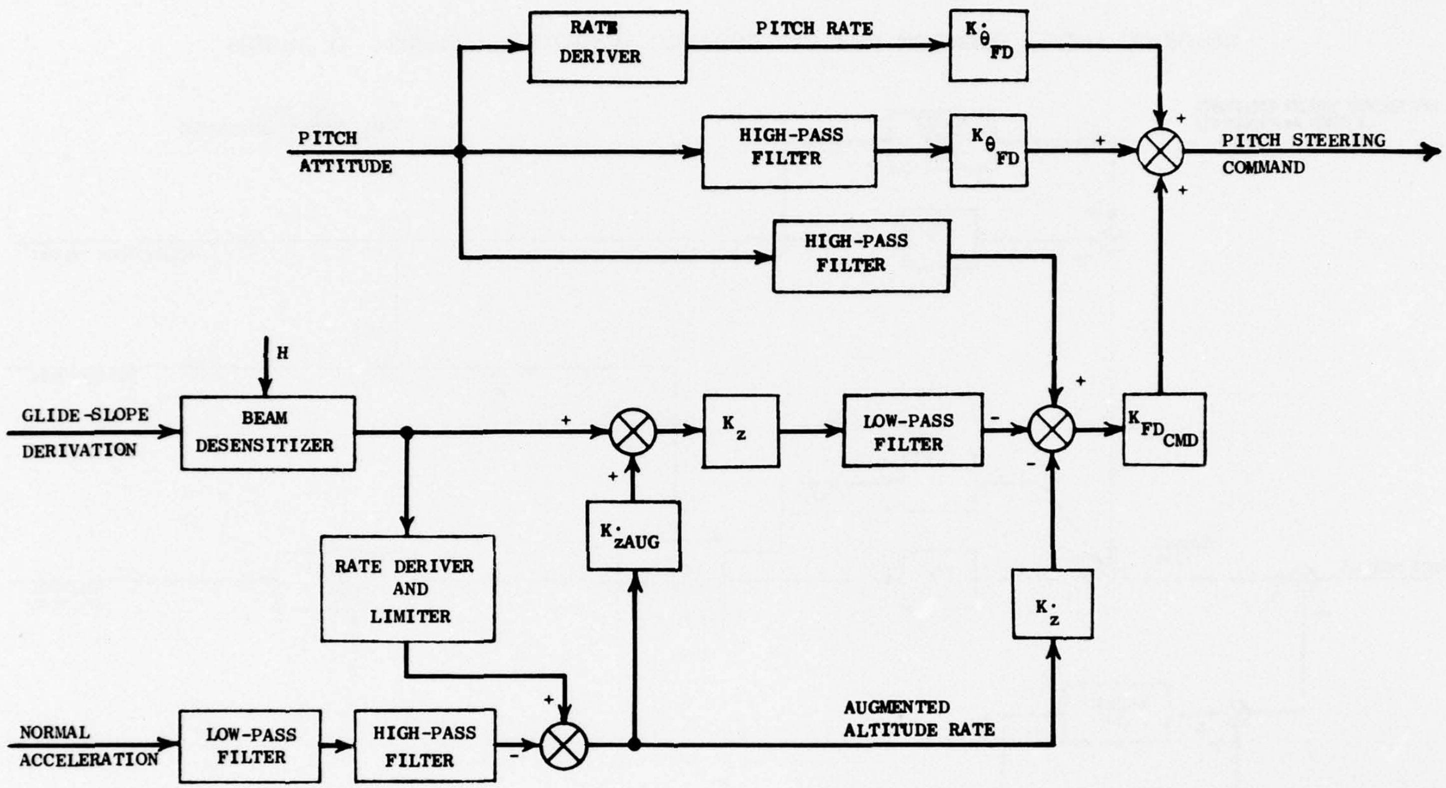


FIGURE 40 BASELINE DC-10 FLIGHT DIRECTOR: GLIDE-SLOPE TRACK

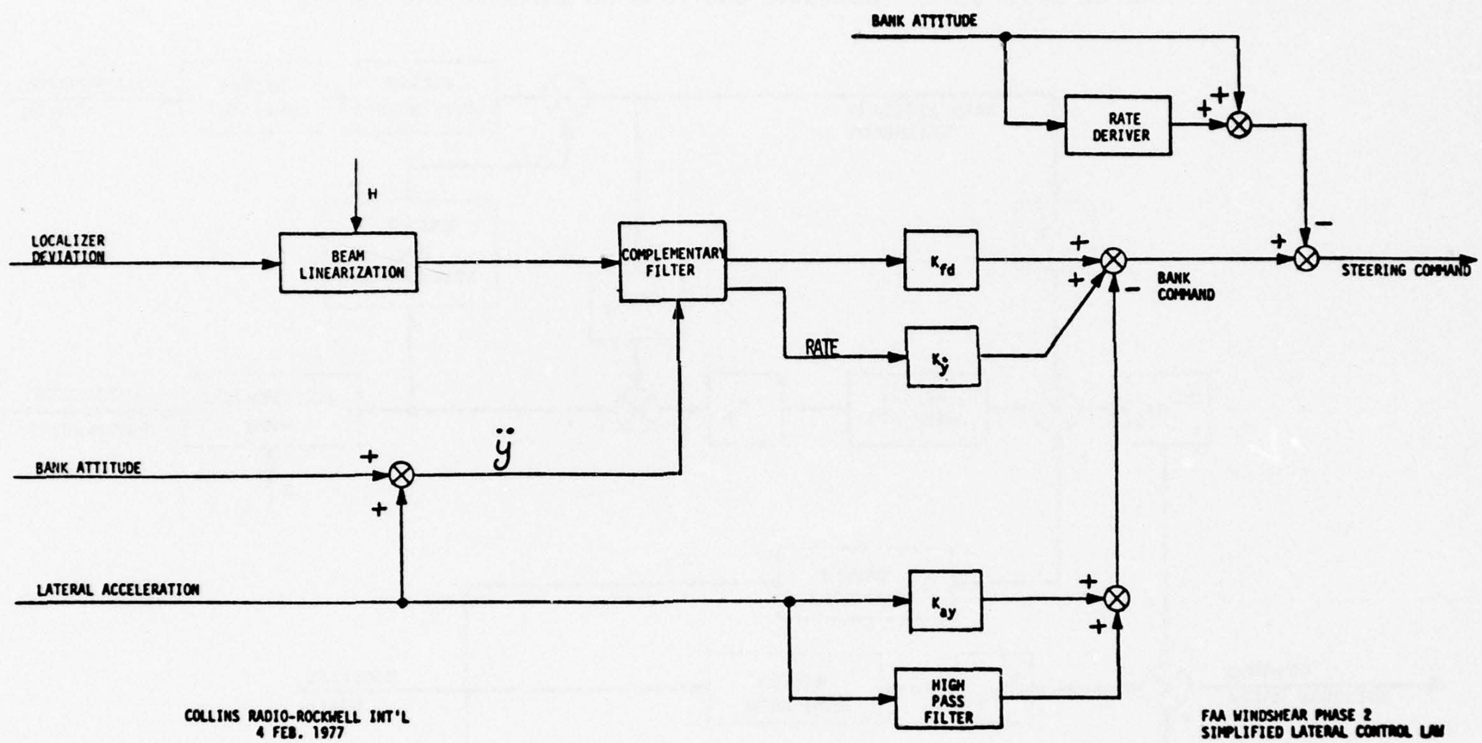


FIGURE 41 SIMPLIFIED LATERAL CONTROL LAW FOR MODIFIED FLIGHT DIRECTOR

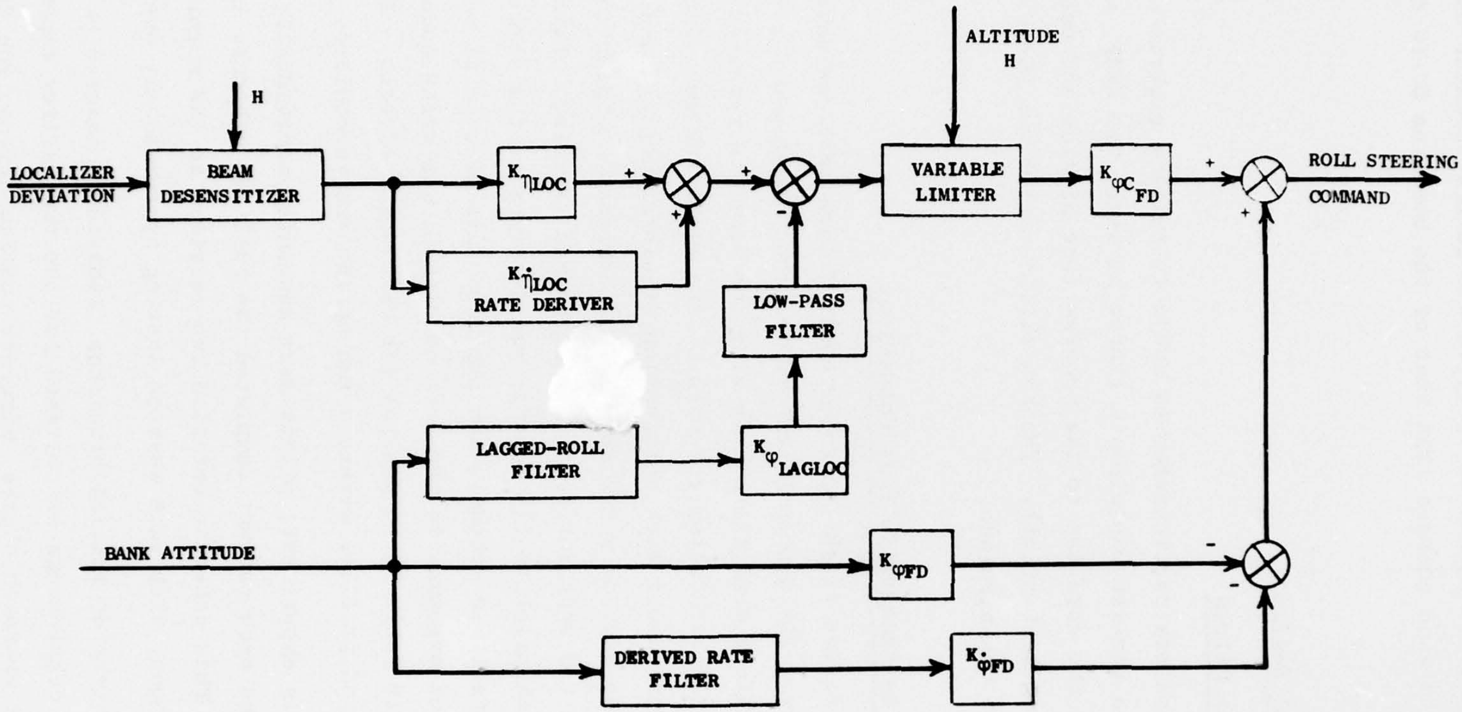


FIGURE 42 BASELINE DC-10 FLIGHT DIRECTOR: LOCALIZER TRACK

also, as in pitch, complementary filtering is used on the localizer deviation. The effect, again, is to drive the lateral command bar with faster response to wind changes than that of the baseline DC-10 flight director.

B. Experimental Design

1. Subject Pilots

Eight pilots participated as subjects in this experiment and included six from earlier experiments (three airline, two USAF, and one FAA) and two who were new to the program (one airline and one Boeing engineering test pilot). The new airline pilot was DC-10 qualified with 600 hours in the airplane.

2. Pilot Assignment to Test Conditions

The modified flight director control laws were evaluated using the same Category I ILS approach scenario as that developed for the earlier experiments. Weather conditions were also the same. A repeated measures design was adopted that called for each of the eight subject pilots to fly three data runs under each combination of aiding concept and wind profile. Prior to each data run series on a designated aiding concept, pilots completed two runs for familiarization and training. This design thus required each pilot to fly four 14-run sessions in the simulator to complete the overall run schedule and produced data on a total of 384 runs. The order of pilot exposure to the test conditions was again counterbalanced, as shown in Table 7, to control for carry-over effects. Exposure to alternative wind profiles within a run series was randomized.

For this experiment, pilots were scheduled individually rather than in pairs, and each subject completed the full run schedule in one day of testing. This schedule entailed two sessions in the morning and two in the afternoon, with each session lasting approximately one hour.

The pattern of initial briefings, individual session briefings, and post-session debriefings established for the two earlier experiments was followed, and approach charts, aircraft configurations, run data cards, general crew procedures and coordination of data recording

Table 7

ORDER OF SUBJECT-PILOT EXPOSURE TO TEST CONDITIONS IN EXPERIMENT 3

	Run Series			
Pilot	1st	2nd	3rd	4th
1	Baseline	Mod FD	ΔW	Mod FD/ΔW
2	Baseline	ΔW	Mod FD/ΔW	Mod FD
3	Mod FD	Baseline	Mod FD/ΔW	ΔW
4	Mod FD/ΔW	Baseline	Mod FD	ΔW
5	Mod FD	ΔW	Baseline	Mod FD/ΔW
6	ΔW	Mod FD/ΔW	Baseline	Mod FD
7	ΔW	Mod FD/ΔW	Mod FD	Baseline
8	Mod FD/ΔW	Mod/FD	ΔW	Baseline

activities were the same. Since the primary concern in this experiment was centered on flight path following by flight director reference, pilots were briefed to remain head-down until they were 100 feet above the runway. They were also instructed to do their best to complete the approach to 100 feet and to simply announce any go-around decision above that altitude. At 100 feet, the pilot transitioned to visual reference for the landing maneuver or execution of the go-around. For this experiment, run data printouts were modified to include six new measures:

(1) RMS vertical offset in feet, derived for the 800-to-100-foot approach segment.

(2) RMS lateral offset in feet, derived for the same segment.

(3) RMS pitch steering bar displacement, in bar widths, derived for the same segment

(4) RMS bank steering bar displacement in bar widths, same segment.

(5) RMS elevator displacement, in degrees, same segment.

(6) RMS aileron displacement, in degrees, same segment.

C. Results and Discussion

1. Approach and Landing Outcomes

Summary plots of approach and landing outcomes for each combination of aiding concept and wind profile are presented in Figure 43. The slight trends toward improved performance using the modified flight director (MFD) on the No Shear and Inversion profiles are not statistically significant for either the 100-foot point or at touchdown. Pilot management of the Frontal Shear appears to be somewhat better under baseline conditions, but the differences shown, as tested by the Cochran Q test, do not reach significance at the 0.05 probability level.

The only substantial improvements over baseline performance shown in Figure 43 are the higher proportions of within-limit approach outcomes at 100 feet under the Thunderstorm shear condition. This improvement is significant at less than the 0.01 probability level for both versions of the MFD--i.e., with and without the ΔW-based speed command. Landing outcomes are also significantly better than baseline for the MFD/ΔW display on this wind profile ($p < 0.01$) but not when the MFD is used without ΔW ($p < 0.10$).

Figure 43 shows substantial improvement in baseline performance on the more severe Frontal and Thunderstorm shear conditions in comparison to approach and landing outcome reported for the two earlier experiments. Since six of the eight subject pilots had prior exposure to these wind profiles in earlier experiments, it is reasonable to assume that this result is attributable in some degree to learning effects. However, an important difference in pilot procedure was adopted for this experiment in that pilots were briefed to remain head-down and fly the command steering information down to 100 feet. Some of the improvement in baseline performance may therefore be attributable to this difference in procedure. This change in procedure may also have been a factor in the generally better performance when the MFD was used; however, the contrasts with baseline performance in this experiment would not be affected.

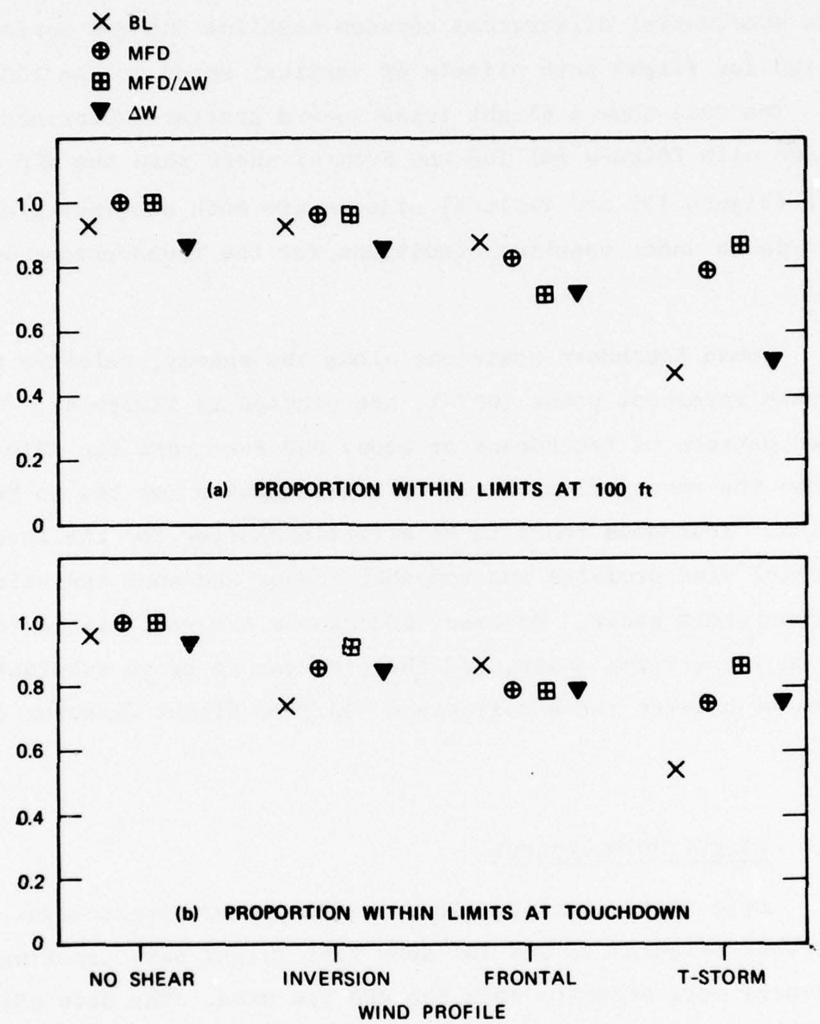


FIGURE 43 SUMMARY OF APPROACH AND LANDING OUTCOMES FOR MODIFIED FLIGHT DIRECTOR

Appendix F contains scatter plots of the approach-outcome positions for Frontal and Thunderstorm profiles.

Summary data plots for the flight situation parameters underlying approach and landing outcomes are presented in Figures 44 through 47. No substantial differences between baseline and MFD performance are indicated for flight path offsets or vertical speed at the 100-foot point. The data show a slight trend toward greater excursions below the glide path (Figure 44) for the Frontal shear when the MFD is used. Lateral (Figure 45) and vertical offsets are both somewhat greater and more variable under baseline conditions for the Thunderstorm wind profile.

Mean touchdown positions along the runway, relative to the glide path intercept point (GPIP), are plotted in Figure 47. The expected pattern of touchdowns at about 500 feet past the GPIP (1500 feet down the runway from threshold) is indicated for the No Shear condition. Touchdown tends to be a little shorter for the Inversion and Frontal wind profiles and somewhat longer and more variable for the Thunderstorm shear. However, touchdowns are well within longitudinal limits on a one-sigma basis, and there appear to be no substantial differences between the baseline and modified flight director on this measure.

2. Flight Path Control

Data plots on glide slope and localizer displacement during the approach (Figures 48 and 49) show that flight path tracking was consistently more accurate when the MFD was used. The data points in these plots are root mean square (rms) deviations from glide slope and localizer over the 800-to-100-foot approach segment that have been averaged over the 24 data runs for each of the 16 combinations of aiding concept and wind profile. Variability across data runs is again indicated by the lines extending above and below the coded data points to show one-sigma (standard deviation) values.

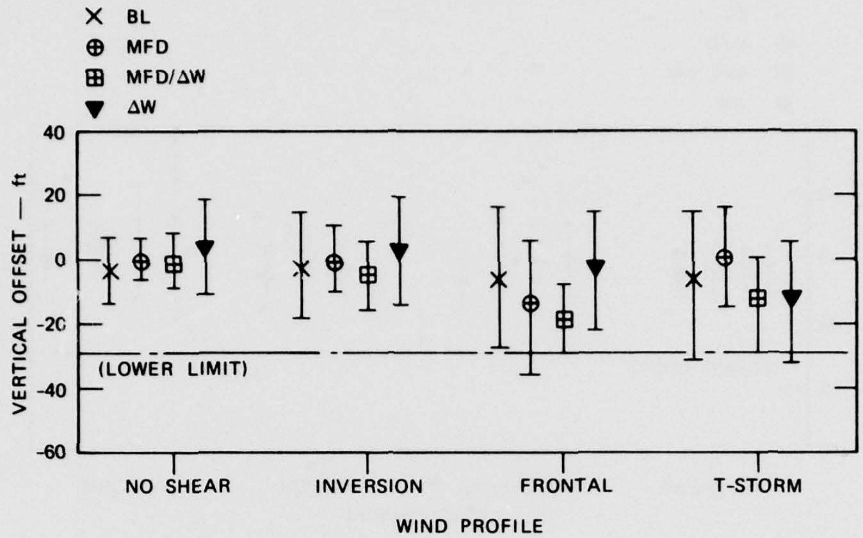


FIGURE 44 GLIDE PATH DISPLACEMENT AT THE INNER MARKER

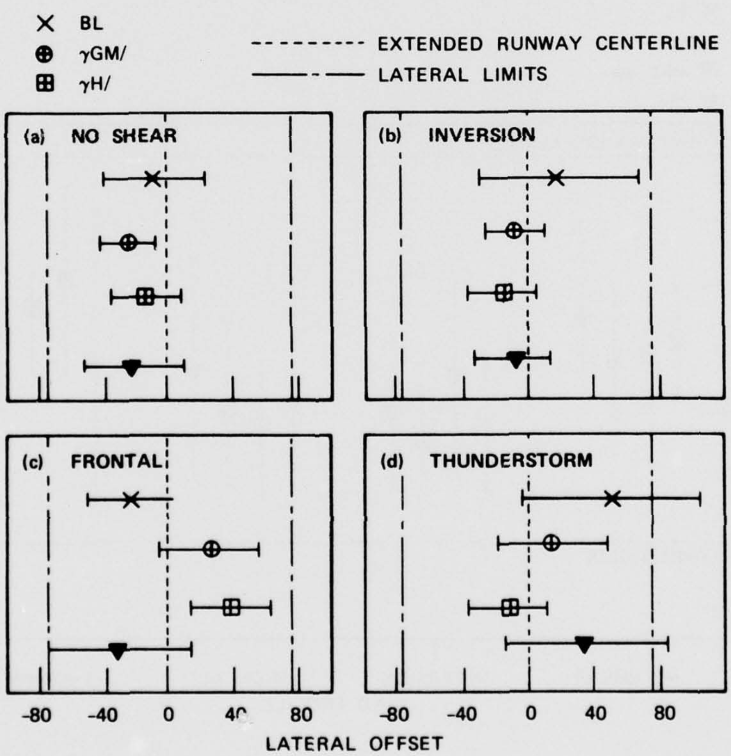


FIGURE 45 LATERAL DISPLACEMENT AT THE INNER MARKER

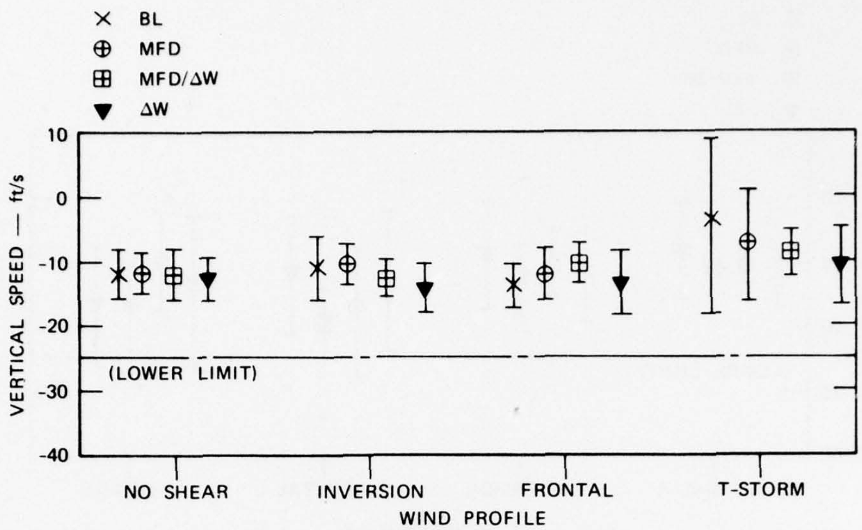


FIGURE 46 VERTICAL SPEED AT THE INNER MARKER

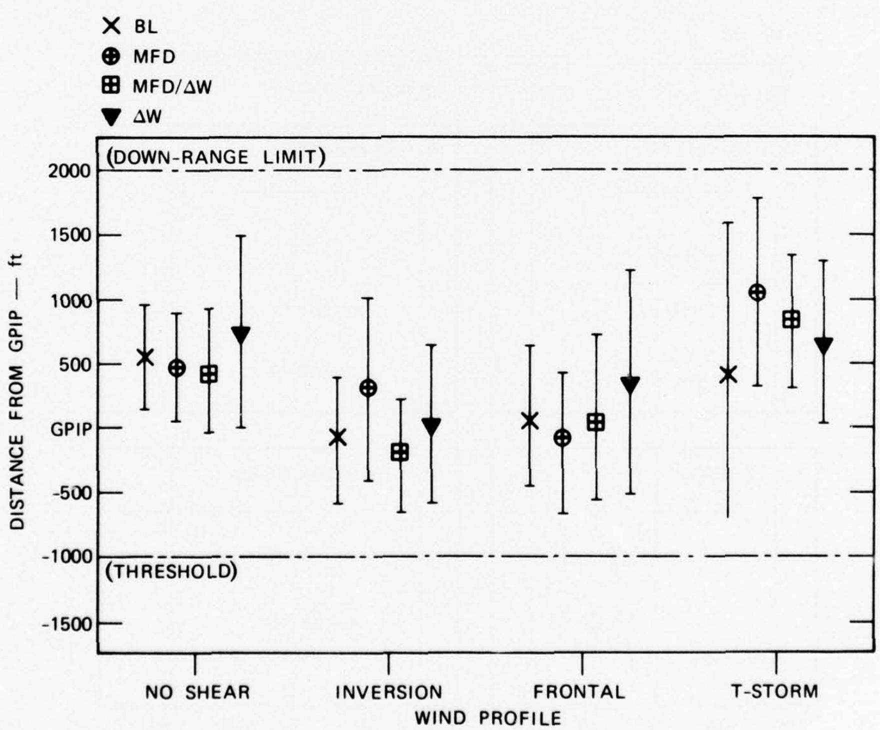


FIGURE 47 TOUCHDOWN POSITION ALONG THE RUNWAY

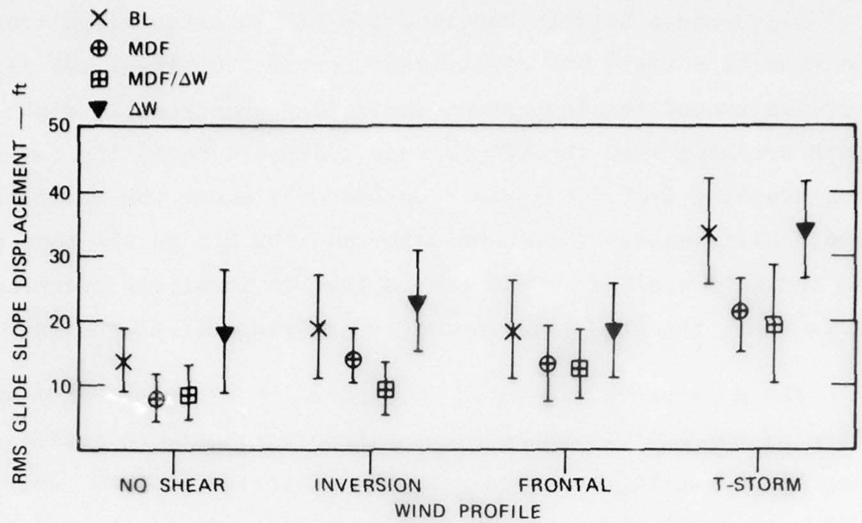


FIGURE 48 MEAN VARIATION IN GLIDE SLOPE TRACKING OVER THE 800-TO-100-FOOT APPROACH SEGMENT

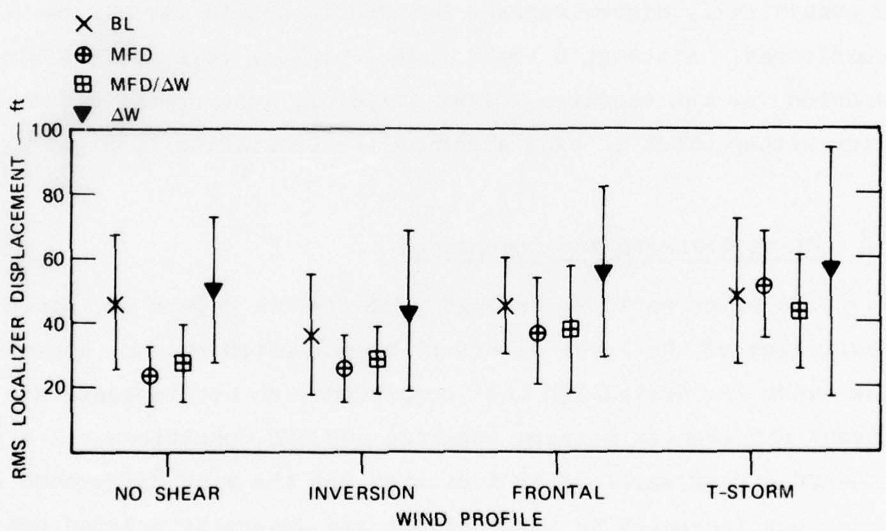


FIGURE 49 MEAN VARIATION IN LOCALIZER TRACKING OVER THE 800-TO-100-FOOT APPROACH SEGMENT

Differences between baseline and MFD in glide slope tracking, based on Dunnett's test, are significant at the 0.05 level for all wind profiles except the Inversion, indicating consistently tighter glide path tracking when the MFD is used. Significantly tighter localizer tracking ($p < 0.05$) was recorded only under the No Shear condition. Differences between baseline and the MFD on the wind shear profiles indicate a slight trend toward tighter localizer tracking when the MFD is used, but the differences are not statistically significant.

The data plots presented in Figures 50 and 51 provide an indication of how closely the subject pilots were able to follow the pitch and bank steering commands using the baseline and MFD control laws. Average pitch steering bar displacements were on the order of one bar width for the No Shear condition and increased in steps to about three bar widths on the Thunderstorm wind profile. The more active and more abrupt changes in pitch steering represented on the MFD were apparently more difficult for the pilots to track, as indicated by the consistently higher command bar displacements for all of the wind conditions. Although a trend toward tighter command following is indicated for the baseline flight director, none of the differences shown for either pitch or bank steering are statistically significant.

3. Pilot Workload and Acceptance

The pilot workload ratings presented in Figure 52, based on pilot estimates of the level of effort they applied on each approach sequence under the designated test conditions, do not indicate any significant differences between baseline and MFD conditions. A slight trend toward higher workload is indicated for the wind difference (ΔW) technique, but increases in pilot effort are generally related only to the severity of the wind profile and do not differ across aiding concepts.

In this experiment, more objective indicators of pilot workload were recorded to augment the pilot ratings. Figure 53 presents the average magnitude of elevator deflections over the 800-to-100-foot

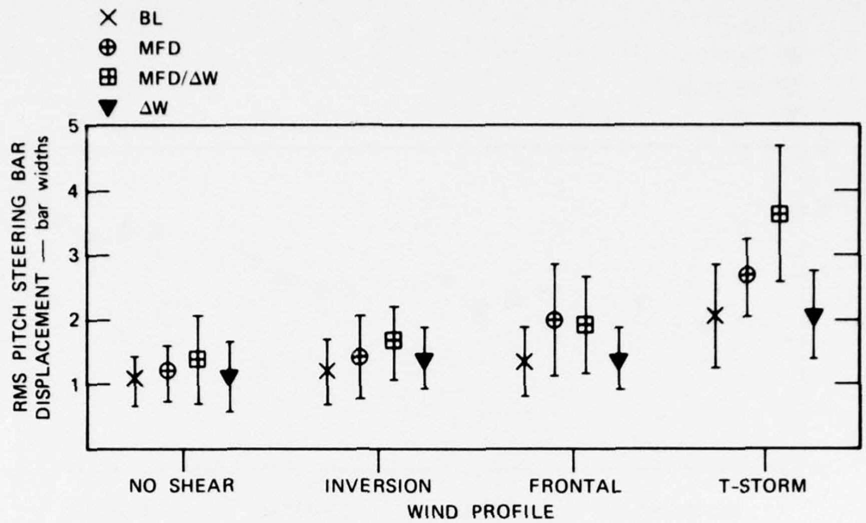


FIGURE 50 MEAN VARIATION IN PITCH STEERING BAR DISPLACEMENTS OVER THE 800-TO-100-FOOT APPROACH SEGMENT

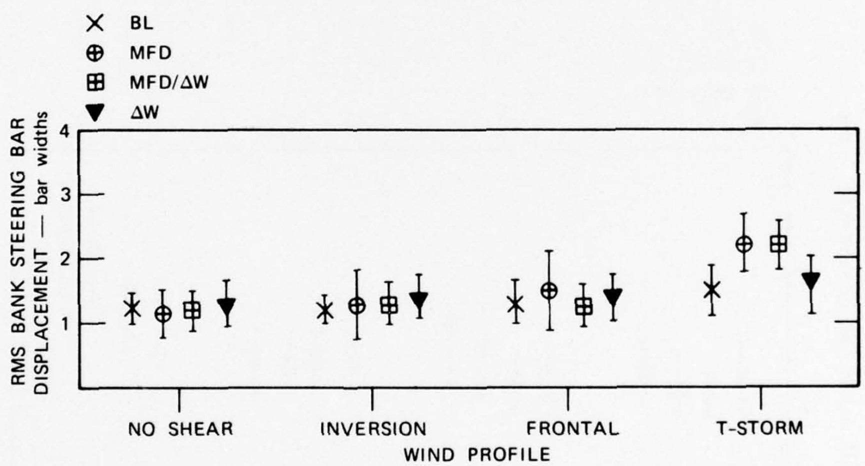


FIGURE 51 MEAN VARIATION IN BANK STEERING BAR DISPLACEMENTS OVER THE 800-TO-100-FOOT APPROACH SEGMENT

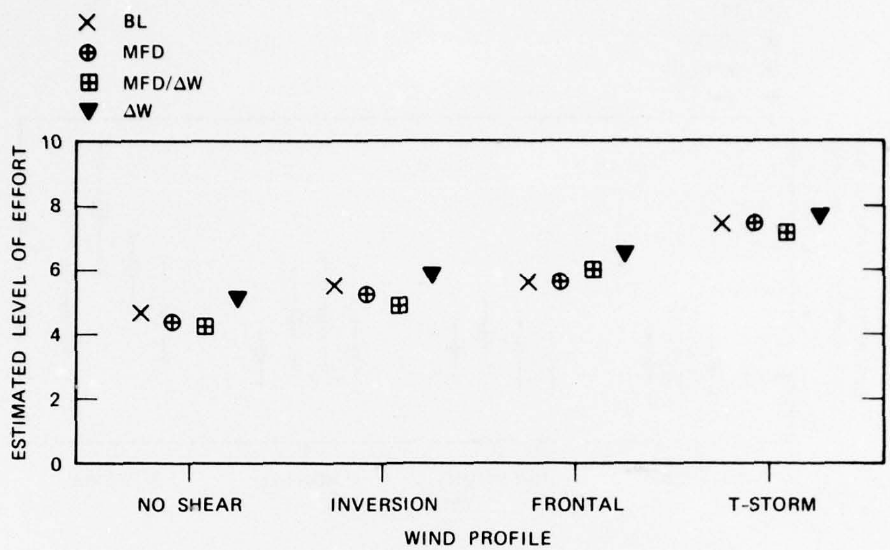


FIGURE 52 MEAN PILOT WORKLOAD RATINGS, EXPERIMENT 3

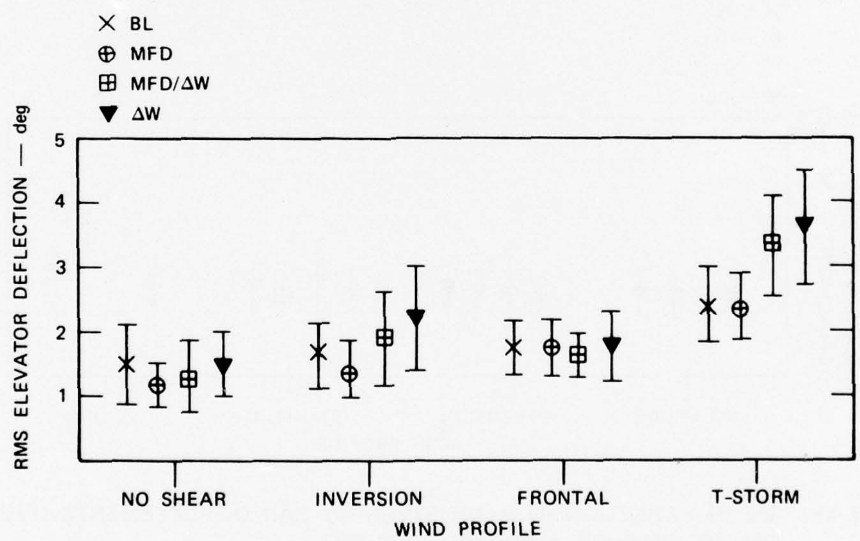


FIGURE 53 MEAN VARIATION IN ELEVATOR DEFLECTIONS OVER THE 800-TO-100-FOOT APPROACH SEGMENT

approach segment as an indication of control column activity. No appreciable differences between baseline and MFD conditions are apparent in pitch control activity on any of the wind profiles. The generally higher levels of elevator deflection shown for the Thunderstorm profile are probably due to the turbulence. Differences across aiding concepts for this shear condition appear to be consistently associated with the ΔW technique and not with differences between baseline and MFD control laws.

Figure 54 presents the average magnitude of aileron deflections over the same approach segment as an indication of control wheel activity. Somewhat greater activity is indicated here for the baseline condition on all shear profiles except the Thunderstorm. This finding suggests that the improved lateral tracking shown earlier for the MFD condition was accomplished with smaller or less frequent control wheel inputs from the pilot. The comparatively higher aileron activity shown for the Thunderstorm shear for all aiding conditions is probably again due to the higher turbulence levels applied on this wind profile.

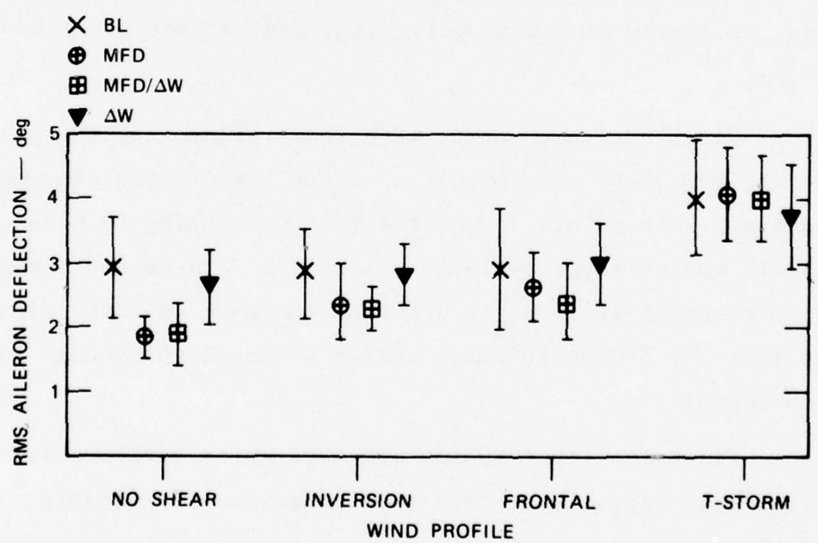


FIGURE 54 MEAN VARIATION IN AILERON DEFLECTIONS OVER THE 800-TO-100-FOOT APPROACH SEGMENT

Pilot acceptance ratings for the aiding concepts tested in the experiment are given in Table 8. All of the aids were rated higher than baseline and it is interesting that pilots expressed greater confidence in the MFD when the ΔW speed command was also available. The high acceptance ratings obtained for the ΔW technique indicate pilot preferences for some form of improved airspeed management in the wind-shear environment. However, the performance data presented earlier do not clearly support pilot confidence in the ΔW speed management technique.

D. Pilot Critique of the Aiding Concept

1. Modified Flight Director

When the modified control laws were applied, the pitch steering bar was considerably more active in the turbulence and downdraft conditions and it appeared to react more quickly to excursions from the glide slope. Pilots often commented that the pitch bar on the standard flight director seemed to lag behind glide slope deviations and noted the contrast using the MFD, which appeared to precede, or change simultaneously with, indications of glide slope deviation.

Under the more active shear conditions, the MFD pitch bar called for immediate and sometimes rather large pitch changes of 8 to 10 degrees. Some pilots found it rather unsettling to make pitch changes as quickly and as large as those called for. In general, the roll steering commands appeared to act much the same on both flight directors except that the MFD would react faster to an abrupt change in the lateral wind component.

Pilot reactions to the MFD were quite varied. All of the pilots felt that both flight directors were effective and flyable. Comments on the MFD ranged from a firm assertion that the pitch command was too active to fly smoothly, to a statement that little or no difference was noticed. The pilot making the latter statement was exceptionally precise and tended to keep the command bars closely centered, so he did not see excessive activity or wide excursions on the MFD.

Table 8

PILOT ACCEPTANCE RATINGS--EXPERIMENT 3

	Aiding Concept			
Pilot	Baseline	Mod/FD	Mod/ΔW	ΔW
1	5	5	5	5
2	4	4	3	4
3	4	4	5	4
4	3	4	4	4
5	2	3	4	3
6	4	4	5	5
7	1	4	3	3
8	1	1	4	1
Total	24	29	33	29
Average	3.0	3.6	4.1	3.6

Most of the pilots expressed a clear preference for the more responsive MFD steering commands. Some were concerned that pilots might not accept the more active steering commands for routine use on the line, but felt that acceptance would be positive after sufficient training and familiarization with the importance of quicker indications and pilot action in the shear environment. One pilot suggested a switch for selecting the quickened steering commands when wind shear was anticipated, thus allowing more conventional damping to be applied at other times.

2. Modified Flight Director with ΔW Speed Commands

Pilot reaction to the addition of the ΔW based airspeed command was generally favorable. They reported no difficulty with following the varying speed command, and most of them felt that the speed pad called for in the head wind shearout condition enabled them to do a better job of flying through the shear. Some of the pilots reported that the use of the ΔW technique diverted their attention from the

demanding task of following the quickened MFD steering commands. Others felt that the quicker, sometimes jerky movements of the steering bars always caught their attention, even when they were concentrating on tracking the moving airspeed command.

E. Conclusions

Data obtained in this experiment support the following conclusions:

(1) Approach and landing outcomes using the MFD were substantially better than baseline only for the Thunderstorm wind profile.

(2) Glide slope tracking was consistently more accurate than baseline, across all wind shear conditions, when the MFD was used; only a slight trend toward more accurate localizer tracking was indicated.

(3) Pilot ability to follow the more abrupt and rapidly changing pitch steering commands on the MFD did not differ significantly from baseline.

(4) No substantial changes in pilot workload over baseline were indicated for the MFD in either pilot ratings or measures of control activity.

(5) Pilots expressed greater confidence in their ability to cope with wind shear when the MFD was used, especially when it was paired with the ΔW-based airspeed management technique.

(6) Pilot ability to manage the shears was not substantially better than baseline when the ΔW-based airspeed management technique was used.

(7) Pilots expressed some concern about the operational acceptance of the more active MFD steering commands, but most of them felt that with sufficient training and familiarization the quickened steering commands would be preferred and that they would contribute to improved performance in the low-level shear environment.

VI GENERAL DISCUSSION*

A. Quality of the Simulation

The Douglas simulator was very good; the motion system was excellent. In general, the pilot reports were very favorable regarding the quality of the simulation.

There were two complaints from a minority of the pilots:

(1) "Simulator too sensitive in roll axis." This seems to be a universal remark when simulators are compared to airplanes. It was observed that regardless of this objection nearly all pilots flew the simulator well after a very short familiarization time. The tendency was to overcontrol in the roll axis for one or two runs and then settle down to normal flying.

(2) "The stabilizer pitch trim didn't feel like the airplane and I had to use more elevator force than I was used to." This was true. In the airplane the pilot definitely "feels" the unloading of the stick forces as he trims the stabilizer to the neutral position. In this simulator this "unloading feel" was absent. The pilot trimmed more with a cut-and-try technique. Very few pilots felt that this feature had any effect on their performance.

As an aside, it should be noted that trimming in a turbulent wind shear environment can be touchy business. It was observed that the average tendency here is to trim too much and then find that it all has to be retrimmed the other way. The pilots who trimmed least in the more violent profiles appeared to have the greatest success. One of the most proficient and experienced pilots in the experiment advised that he used no trim at all bounding around in the thunderstorm profile. This, of course, requires considerable elevator force at times, but it keeps the pilot from running short of elevator at critical times. It is possible on some of our jet transports to trim the big stabilizers to the point at which the elevator is no longer effective. If the

*This section contributed by Captain William O. Nice.

pilot does try to keep the airplane constantly trimmed to a neutral position he should be cognizant at all times of the position of the stabilizer to assure himself of ample elevator when he needs it. This is especially important when approaching for a landing in turbulent, rapidly changing conditions.

It is felt that this simulation argues strongly for the merits of motion in a test of this type. Because of a breakdown, two of the pilots were forced to complete their runs using the simulator as a fixed base vehicle. It was observed, and their comments agreed, that their performance was more natural and they felt more at ease with the motion. Profiles with turbulence reflected only in the jiggling of instruments without the accompanying motion are simply not realistic.

The simulation of the various aiding concepts was well done throughout the experiment. The wind profiles were accepted as realistic by all the participants, even though most said they never actually experienced any conditions as severe as some of these profiles.

The following are general observations, from the right seat, of the effectiveness and ease of use of the various aiding concepts: The use of ground-speed information to cope with wind shear was somewhat new, but once the basic idea became clear the pilots accepted it readily. Display via the green pointer (GNS-1) was rather natural. On the other hand the digital readout (GNS-2) was somewhat outside the normal scan region and required a little extra thought. The ground speed had to be read and mentally compared with the planned minimum ground speed, and a decision then had to be made whether to add or reduce thrust to adjust the desired ground speed to the reference value. This is something new in the way of technique. The pilots are used to flying needles to fixed references as used in the "green needle" ground speed technique.

One deficiency in these ground speed concepts was our failure to foresee the value of the Fast-Slow indicator on the ADI. When the minimum ground speed was the controlling factor, the Fast-Slow command had to be ignored. If the Fast-Slow were programmed to always reflect the difference between the indicated airspeed and the "critical"

approach reference speed, whether it was the pilot-selected V approach or the reference ground speed, the technique would be simplified, because no mental calculations would be required. The approach would be done as the pilot is used to doing it and the digital readout would be merely advisory. In our view the wind difference (ΔW) concept, as programmed with the automatic speed-loss pad and the valid Fast-Slow indicator on the ADI, was expected to be the most promising technique of the program. Despite the poor performance, we feel that this concept still has considerable merit. Perhaps the problem comes with the new idea of trying to control the speed to a moving reference. To do this requires the pilot to devote more time to watching the speed displays. He is afraid the bug will move quickly away from his airspeed needle and he watches it closely to keep on top of his speed control. He can't check it with a glance for a trend, as he normally does when controlling his indicated airspeed needle to a fixed reference. Perhaps this moving reference bug concept, to be fully tested, requires more training to set up a new habit pattern.

It is felt that the simulation of flight path angle was done as well as the state of the art allows. The flight path angle was displayed clearly in the pilot's normal instrument scan pattern. The activity of the display seems to be the critical factor. Both algorithms caused the instrument to be too active to use as a control instrument. Effective use of the flight path angle required fine pitch changes of 1, 2, or 3 degrees, but the pilots were not able to do this in any kind of turbulence. Most airline pilots thought the pitch attitude scale was too restricted for fine attitude corrections. This attitude director's 30° nose-up position was about equal to a 20° nose-up position on the normal airline instrument.

The baseline flight director in the DC-10 is a sophisticated unit and already includes some acceleration input. There were, however, performance differences between it and the Collins modified steering commands, the most noticeable being the quickened response of the modified unit.

It appeared that, because of the augmentation present in the quickened director, the desired path was followed more closely. When the new director called for a correction it did so quickly; and, because of its quickness, it got the pilot's attention. The pilot thus tended to respond sooner and therefore held more precisely to his desired path. It appears that a more responsive flight director has good possibilities in aiding the pilot to navigate through adverse environments.

B. Scheduling

An experimental program such as this works best if two pilots at a time can be scheduled and brought in to work through the tests together. This allows time for alternating the subjects between the simulator sessions and the briefing and debriefing sessions. It also allows the subject a needed break. Experimental approaches one after another through low-level wind shear conditions require a high degree of concentration. Forty-five minutes to one hour of this type of work appears to be the maximum time that can be used productively. After that, fatigue sets in and the quality of the approach deteriorates. The pilot needs a break to regain his concentration and objectivity. The best number of approaches per session appears to be about 12. Two sessions per day of 12 runs each would be ideal, but three sessions of 12 runs each per man would make the program more efficient and still be within the productive capabilities of the pilots.

Pilots, especially airline pilots, are very receptive to this type of program and can be recruited easily. However, their schedules are made out on a monthly basis and are usually set 10 days to 2 weeks ahead of the first of each month. They can be scheduled to participate if enough advance notice is given and the schedule holds firm. Problems develop when recruiting is attempted on short notice or when the simulator breaks down. A breakdown in the simulator usually means the loss of the pilot for that month. The pilots who volunteer for this sort of effort are usually quite busy and have many demands on their time. It is easy to get a pilot for one day, but it becomes progressively harder

as one tries to schedule him for 2, 3, or 4 days at a time. It can be done, but must be accomplished through advance planning. The schedule must also take into account the work day of simulation support workers and must fit into their scheme of things as closely as possible.

All recruiting of subject pilots should be done from one location. Considerable coordination is required to schedule pilots for a program of this type, and it requires the work of one man for several days to implement a successful recruiting program. To forestall problems, one person should do all the recruiting, and all volunteers and recommendations should flow through his office, where the final selections and schedules are made.

C. Pilot Selection

The pilots that have been selected for this program in the past have been, for the most part, the "pick of the crop." They are the volunteers, the most highly motivated and skilled men in their profession. This has been very good for the program up to this point. It has helped greatly in shaking the program down to the point where some concrete assistance for the average pilot can be forthcoming. The pilots have accomplished the task of narrowing the search down to the most useful and practical of the many concepts tested. It has been pointed out that this select group of pilots probably need the help less than the average pilot, and consequently the selected aiding concepts probably do less good for them than they will for the average person.

Now that the concepts have been narrowed down and a final selection is to be made, it is felt that a new or larger group should be selected, if possible from active, non-management line pilots.

D. Learning Factors

The training effect must be recognized. It can be minimized but not completely overcome. There is no question that several of the subject pilots have had sufficient exposure to the wind profiles, as used in this experiment, to be familiar with them and to anticipate the

necessary action. This training effect was guarded against by randomizing the orders in which pilots flew the various concepts, as well as the order of the wind-shear profiles. The profiles themselves included some No-Shear profiles that felt and started out like the more severe wind shears. The fact that occasionally one of the pilots would initiate a go-around on one of these innocuous profiles, for no apparent reason, illustrated the assumed recognition and anticipation that some pilots could not entirely avoid.

The pilots were instructed to start each run fresh and treat each one objectively. They all attempted to do this and succeeded to a great extent. However, it is felt that any further experimentation would be enhanced by having a new and more varied selection of shear profiles.

VII CONCLUSIONS AND RECOMMENDATIONS

This section summarizes the major conclusions supported by the results of Phase 2 testing for each of the aiding concepts evaluated. The discussion of each concept includes a brief statement of recommendations regarding further development and testing.

A. Ground Speed Displays

The availability of ground speed information, together with pilot use of the minimum preplanned ground speed technique, is considered to be the most promising near-term aid for the low-level shear encounter. This technique produced substantial improvement in approach and landing outcomes, relative to conventional airspeed management, on the more severe Frontal and Thunderstorm wind profiles. The technique was readily assimilated by the pilots, and is considered to be effective and practical for routine use in airline operations.

The manner in which ground speed information is displayed to the pilot is an important performance factor and needs additional study. Improvement over baseline performance was realized only when the two-pointer display (GNS-1) was used; pilot performance using the digital readout of ground speed (GNS-2) did not differ significantly from the conventional (baseline) technique. The two-pointer display was generally considered to be easy to interpret, and provided the additional advantage of showing the along-track wind situation--i.e., head wind/tail wind component, throughout the approach. However, in the more dynamic wind-shear environments, pilots could experience some difficulty in clearly distinguishing the two pointers and in deciding which limiting speed to maintain (i.e., minimum ground speed or target approach speed).

Additional development and testing of the ground speed display and use concept is recommended. Human engineering development is needed to achieve a better integration of ground speed display elements with the conventional instruments. Consideration should also be given to expanding the use concept to include more direct support for pilot assessments of wind shear effects and for making timely approach continuation or go-around decisions.

B. Wind Difference Displays

No substantial improvement in pilot performance was recorded when the wind difference (ΔW) technique was used. Pilots expressed positive acceptance of the ΔW-based airspeed command concept and felt that ΔW information provided a useful indication of potential shear. However, performance did not differ significantly from baseline when the ΔW technique was used, either in the first experiment or in the third when the technique was simplified by omitting the digital readout of ΔW.

Pilots were generally unable to integrate the digital readout of ΔW into their scan pattern because of the demands of flight director and speed command tracking on their attention. When they attempted to use the ΔW readout to assess the potential shear, performance on the primary tracking tasks was degraded.

Additional development and testing of the ΔW technique is not recommended.

C. Flight Path Angle Displays

No consistent improvement over baseline performance was recorded when either type of flight path angle (FPA) display was used. In some instances, approach and landing outcomes were substantially worse than baseline when FPA was available, indicating that attempts to use FPA might degrade rather than enhance pilot management of the shear encounter.

Both ways of computing FPA (ground referenced and hybrid) produced displays that were too active for effective use under the more dynamic

shear and turbulence conditions for either flight path control or wind effect monitoring. When the display was reasonably stable, pilots considered FPA to be very helpful in providing lead information on imminent departures from the glide slope. However they were not able to effectively integrate this information into the flight path control task using either pitch steering commands or the raw glide slope deviation indicator.

Further development and testing of panel displays of FPA is not recommended. The fundamental problem of producing an FPA display that is sufficiently responsive to wind effects and, at the same time, stable enough for monitoring or control has not been resolved. The development of effective display concepts will also entail considerable additional study.

D. Modified Flight Director

Substantial improvement in approach and landing outcomes was recorded for this aiding concept against the Thunderstorm wind profile. Glide slope tracking was consistently more accurate than baseline when the modified flight director (MFD) was used on all shear conditions and, while pitch steering commands on the MFD were noticeably quicker and of greater magnitude than the conventional flight director, the more accurate tracking was achieved with no substantial increase in pilot workload. Some of the pilots were initially concerned about the more active MFD pitch steering commands, but after further exposure most of them preferred the MFD to the less responsive conventional flight director.

Further development and testing of the MFD control laws is recommended. Interactions between pitch control and airspeed management techniques should be investigated and the potential benefits of incorporating a coordinated thrust command into the MFD control laws should be tested. Consideration should also be given to using the MFD with the ground speed display or some other form of wind-shear alerting information.

E. Test Conditions

In these experiments, performance was tested against only three wind-shear profiles, which certainly do not span the full range of possible wind conditions. It is recommended that an expanded set of wind profiles, to include a wider variety of wind shears with different degrees of severity, be developed and that subsequent testing of aiding concepts be done against the expanded set.

The experiments were designed to give measures of aiding-concept performance relative to baseline, so a comparatively small number of subject pilots was adequate. It is recommended that subsequent testing of the techniques that have shown promise be directed toward an absolute (as opposed to relative) performance validation. This will involve testing with a considerably larger group of pilots.

Appendix A

WIND PROFILES FOR PHASE 2 SIMULATION TESTS

Table A-1

WIND PROFILE-- "NO-SHEAR" CONDITION A*

Altitude (x100 ft)	Along-Track† (kt)	Cross Track‡ (kt)
0.20	0.0	0.0
15.0	-20.0	-20.0

Note: Linear interpolation is used to obtain values between 20 and 1500 ft pts.

* Although this profile is equivalent to 1.3 kt/100 ft, for purposes of this simulation it will be considered "no-shear".

† + = Head wind.
- = Tail wind.

‡ + = Wind from right, as sensed from aircraft.
- = Wind from left, as sensed from aircraft.

Table A-2

WIND PROFILE--"NO-SHEAR" CONDITION B*

Altitude (x100 ft)	Along-Track† (kt)	Cross-Track‡ (kt)
0.20	+7.5	+3.0
15.0	+22.0	+10.0

Note: Use linear interpolation between 20 and 1500 ft.

* See Profile 1a.

† + = Head wind.
- = Tail wind.

‡ + = Wind from right, as sensed from aircraft.
- = Wind from left, as sensed from aircraft.

Table A-3

TURBULENCE PARAMETERS--"NO-SHEAR" CONDITION B

Altitude (x100 ft)	σu (kt)	σv (kt)	σw (kt)	Lu (ft)	Lv (ft)	Lw (ft)
0.20	0.65	0.65	0.09	105.7	49.7	10.4
6.0	0.25	0.25	0.06	530.9	445.6	318.0

Note: Use Linear interpolation between 20 and 600 ft.

σ = Standard deviation of wind intensity.

L = Turbulence scale length.

u = Longitudinal direction.

v = Lateral direction.

w = Vertical direction

Table A-4

WIND PROFILE--INVERSION

Altitude (x100 ft)	Along-Track* (kt)	Cross Track (kt)
0.2	+6.8	0
0.75	+11.6	0
1.5	+19.6	0
3.0	+23.7	0
4.5	+32.4	0
6.0	+30.0	0
7.5	+26.2	0
9.0	+24.6	0
10.5	+22.9	0
12.0	+22.6	0
13.0	+22.3	0
15.0	+22.3	0

* + = Head wind.
  \- = Tail wind.

Table A-5

TURBULENCE PARAMETERS--INVERSION

Altitude (x100 ft)	σu (kt)	σv (kt)	σw (kt)	Lu (ft)	Lv (ft)	Lw (ft)
0.2	0.65	0.65	0.09	105.7	49.7	10.4
0.75	1.63	1.63	0.15	182.0	107.9	39.7
1.5	3.61	3.61	0.25	261.6	173.8	79.5
3.0	4.76	4.76	0.31	370.0	276.5	159.0
4.5	0.50	0.50	0.09	457.9	366.1	238.5
6.0	0.25	0.25	0.06	530.9	445.6	318.0

Notes:

σ = Standard deviation of wind intensity.

L = Turbulence scale length.

u = Longitudinal direction.

v = Lateral direction.

w = Vertical direction.

Table A-6

WIND PROFILE--FRONTAL WIND SHEAR

Altitude (x100 ft)	Along-Track* (kt)	Cross Track† (kt)
0.20	+0.1	+0.6
1.0	+6.8	-1.8
2.0	+13.5	-3.6
3.0	+10.8	-15.5
4.0	-1.9	-22.3
5.0	-18.0	-18.0
6.0	-19.7	-19.7
7.0	-21.4	-21.4
8.0	-22.8	-22.8
9.0	-24.2	-24.2
10.0	-25.4	-25.4
11.0	-26.4	-26.4
15.0	-31.7	-31.7

* + = Head wind.
- = Tail wind.

† + = Wind from right, as sensed from aircraft.
- = Wind from left, as sensed from aircraft.

Table A-7

WIND PROFILE--THUNDERSTORM COLD AIR OUTFLOW

X = 3,000 Feet

Altitude (ft)	Vu* (kt)	Vv† (kt)	Vw‡ (kt)
20	-16.9	3.0	-0.0
150	-19.4	7.5	-0.2
250	-20.1	8.0	-0.7
350	-23.6	9.0	2.2
450	-20.8	10.0	14.7
550	-26.7	11.0	-9.7
650	-13.5	12.0	-9.7
800	-4.6	12.8	-6.5
1200	-4.0	11.2	-3.3
1500	-4.8	10.0	-3.4

X = 1,000 Feet

Altitude (ft)	Vu (kt)	Vv (kt)	Vw (kt)
20	-15.5	3.0	-0.0
150	-20.3	7.5	-0.4
250	-21.4	8.0	-2.5
350	-23.8	9.0	-1.1
450	-26.6	10.0	-2.5
550	-26.0	11.0	-8.0
650	-23.5	12.0	-12.9
800	-5.6	12.8	-7.7
1200	-3.1	11.2	-7.4
1500	-2.3	10.0	-6.1

* + = Head wind.
- = Tail wind.

† + = Wind from right, as sensed from aircraft.
- = Wind from left, as sensed from aircraft.

‡ + = Updraft.
- = Downdraft.

X = Longitudinal distance from touchdown.

Table A-7 (continued)

X = -1,000 Feet

Altitude (ft)	Vu (kt)	Vv (kt)	Vw (kt)
20	-13.2	3.0	0.0
150	-19.9	7.5	0.0
250	-22.2	8.0	-3.6
350	-20.8	9.0	-6.0
450	-25.6	10.0	0.0
550	-28.4	11.0	0.0
650	-23.1	12.0	-11.4
800	-9.1	12.8	-10.9
1200	-2.7	11.2	-8.4
1500	-2.4	10.0	-9.0

X = -3,000 Feet

Altitude (ft)	Vu (kt)	Vv (kt)	Vw (kt)
20	-5.5	3.0	0.0
150	-9.9	7.5	-0.9
250	-10.4	8.0	-6.1
350	-10.4	9.0	-17.9
450	-11.1	10.0	-27.7
550	-7.0	11.0	-30.6
650	-4.1	12.0	-27.0
800	0.0	12.8	-16.6
1200	0.0	11.2	-14.8
1500	0.0	10.0	-14.8

Table A-7 (continued)

X = -5,000 Feet

Altitude (ft)	Vu (kt)	Vv (kt)	Vw (kt)
20	5.5	3.0	-0.0
150	9.9	7.5	-0.9
250	10.4	8.0	-6.1
350	10.4	9.0	-17.9
450	11.1	10.0	-27.7
550	7.0	11.0	-30.6
650	4.1	12.0	-27.7
800	0.0	12.8	-16.6
1200	0.0	11.2	-14.8
1500	0.0	10.0	-14.8

X = -6,000 Feet

Altitude (ft)	Vu (kt)	Vv (kt)	Vw (kt)
20	11.9	3.0	-0.0
150	17.5	7.5	-0.7
250	18.8	8.0	-6.1
350	20.8	9.0	-10.3
450	18.8	10.0	-12.3
550	17.4	11.0	-24.0
650	6.2	12.0	-24.6
800	5.6	12.8	-13.4
1200	2.4	11.2	-14.0
1500	1.5	10.0	-12.3

Table A-7 (continued)

X = -7,000 Feet

Altitude (ft)	Vu (kt)	Vv (kt)	Vw (kt)
20	13.2	3.0	-0.0
150	19.9	7.5	-0.0
250	22.2	8.0	-3.6
350	20.8	9.0	-6.0
450	25.6	10.0	0.0
550	28.4	11.0	0.0
650	23.1	12.0	-11.4
800	9.1	12.8	-10.9
1200	2.7	11.2	-8.4
1500	2.4	10.0	-9.0

X = -8,000 Feet

Altitude (ft)	Vu (kt)	Vv (kt)	Vw (kt)
20	14.5	3.0	-0.0
150	20.8	7.5	-0.4
250	21.5	8.0	-2.6
350	23.1	9.0	-4.1
450	29.0	10.0	2.3
550	28.4	11.0	0.0
650	25.4	12.0	11.9
800	7.8	12.8	9.7
1200	3.2	11.2	8.9
1500	2.4	10.0	7.0

Table A-7 (continued)

X = -9,000 Feet

Altitude (ft)	Vu (kt)	Vv (kt)	Vw (kt)
20	15.5	3.0	-0.0
150	20.3	7.5	-0.4
250	21.4	8.0	-2.5
350	23.8	9.0	-1.1
450	26.6	10.0	+2.5
550	26.0	11.0	-8.0
650	23.5	12.0	-12.9
800	5.6	12.8	-7.7
1200	3.1	11.2	-7.4
1500	2.3	10.0	-6.1

X = -10,000 Feet

Altitude (ft)	Vu (kt)	Vv (kt)	Vw (kt)
20	16.8	3.0	-0.0
150	20.1	7.5	-0.2
250	20.8	8.0	-0.9
350	23.8	9.0	0.0
450	25.5	10.0	6.0
550	25.3	11.0	-12.9
650	20.8	12.0	-12.9
800	4.9	12.8	-8.1
1200	3.3	11.2	-5.6
1500	6.1	10.0	-4.4

Table A-7 (continued)

X = -11,000 Feet

Altitude (ft)	Vu (kt)	Vv (kt)	Vw (kt)
20	16.9	3.0	-0.0
150	19.4	7.5	-0.2
250	20.1	8.0	-0.7
350	23.6	9.0	2.2
450	20.8	10.0	14.7
550	26.7	11.0	-9.7
650	13.5	12.0	-9.7
800	4.6	12.8	-6.5
1200	4.0	11.2	-3.3
1500	4.8	10.0	-3.4

X = -13,000 Feet

Altitude (ft)	Vu (kt)	Vv (kt)	Vw (kt)
20	17.1	3.0	-0.0
150	19.3	7.5	-0.0
250	20.0	8.0	-0.2
350	23.2	9.0	2.2
450	26.6	10.0	-2.5
550	17.8	11.0	-4.4
650	15.6	12.0	-3.0
800	6.6	12.8	-1.9
1200	6.1	11.2	-1.5
1500	5.8	10.0	-0.9

Table A-7 (continued)

X = -31,000 Feet

Altitude (ft)	Vu (kt)	Vv (kt)	Vw (kt)
20	9.6	3.0	0.0
150	19.1	7.5	0.0
250	20.1	8.0	0.0
350	22.9	9.0	0.0
450	26.7	10.0	0.0
550	19.0	11.0	0.0
650	15.8	12.0	0.0
800	7.0	12.8	0.0
1200	6.5	11.2	0.0
1500	6.0	10.0	0.0

Table A-8

TURBULENCE PARAMETERS--THUNDERSTORM COLD AIR OUTFLOW

Altitude (x100 ft)	σu (kt)	σv (kt)	σw (kt)	Lu (ft)	Lv (ft)	Lw (ft)
0.33	3.50	2.80	2.53	123.9	63.4	17.3
1.0	4.05	3.46	3.53	216.7	134.2	53.0
2.0	4.43	3.95	4.35	306.5	213.5	106.0
4.0	4.85	4.50	5.36	433.5	339.6	212.0
6.0	5.11	4.86	6.05	530.9	445.6	318.0

Notes:

σ = Standard deviation of wind intensity

L = Turbulence scale length

u = Longitudinal direction

v = Lateral direction

w = Vertical direction

Appendix B

ON-SITE DATA RECORDING

This appendix lists the flight situation and aircraft state parameters that were recorded on magnetic tape and strip charts during each simulated approach and landing sequence. A brief description of the data elements available on the summary data printout for each run is also provided.

The coordinate system adopted for representing these parameters in the simulation is as follows: The ground-axis system consists of a right-handed orthogonal axis whose origin is attached to the surface of the earth at the intersection of the glide path and the centerline of the runway. As illustrated below, the x_G axis is coincident with the runway centerline and is positive in the direction of the departure end of the runway. The z_G axis points vertically along the g vector and is positive downward. The body-axis system consists of right-handed, orthogonal axes whose origin is fixed at the nominal aircraft center of gravity. Its orientation remains fixed with respect to the aircraft, with the x_B axis taken along the body centerline (positive forward) and the z_B axis taken outward from the belly of the aircraft in the plane of symmetry. The y_B axis is then positive out the right wing.

1. Date Recorded on Magnetic Tape

The digitally logged data were recorded on 9-track 800 BPI digital magnetic tape. The characteristics of the sampling process were as follows:

- Sampling rate was 5 Hz.
- Each parameter was represented as a scaled 16-bit twos-complement number.
- A frame consisted of the 34 parameters listed in Table B-1 below, plus 6 spare locations for a total of 40 16-bit words.

Table B-1

FLIGHT SIMULATION PARAMETERS RECORDED ON MAGNETIC TAPE

Number	Symbol	Description	Engineering Units
1	t	Time code, elapsed time from initiation of run	0.1
2	X	Position coordinates as measured to the aircraft center of gravity, ground-axis referenced.	ft
3	Y		ft
4	Z		ft
5	Ψ_e	Heading angle referenced to the runway heading (positive right of runway heading on approach)	deg
6	θ	Pitch angle (positive nose up)	deg
7	α	Angle of attack (pitch angle minus air-referenced flight path angle)	deg
8	φ	Roll angle (positive right wing down)	deg
9	$\dot{X}$	Ground-referenced velocities, the rate of change of x, y, and x components	ft/s
10	$\dot{Y}$		ft/s
11	$\dot{Z}$		ft/s
12	A_x	Longitudinal acceleration along the x body axis at the center of gravity (positive forward)	ft/s^2
13	A_n	Normal acceleration parallel to the z body axis at the center of gravity (positive up)	ft/s^2
14	$\dot{\theta}$	Pitch rate, angular velocity about y-axis (positive nose up)	deg/s

Table B-1
(Concluded)

Number	Symbol	Description	Engineering Units
15	$\dot{\varphi}$	Roll rate, angular velocity about x-axis (positive right wing down)	deg/s
16	$\dot{\Psi}$	Yaw rate, angular velocity about z-axis (positive nose right)	deg/s
17	W_x	Wind velocity, ground-axis referenced, x, y, and z components	knots
18	W_y		knots
19	W_z		knots
20	IAS	Indicated airspeed	knots
21	GNS	Ground speed after computation as displayed	knots
22	PSB	Pitch and bank steering bars and speed Command as displayed on the pilot's ADI	bar widths
23	BSB		bar widths
24	SC		knots
25	LOC	Localizer and glide slope deviations as displayed	dots
26	GS		dots
27	γ_a	Air-referenced and ground-referenced flight path angles as indicated on the FPA display	deg
28	γ_g		deg
29	N_1	Engine RPM N_1 of the center engine	%
30	Δ_W	Wind difference as computed	knots
31	δTH	Position of the center engine throttle lever	deg
32	δF	Flap position	deg
33	V_{app}	Airspeed bug setting (set by pilot)	knots
34	-	This 16-bit word was reserved for the following binary events: Outer Marker Beacon Light Middle Marker Beacon Light Inner Marker Beacon Light Gear Lowered Main Gear Touchdown Go-around Initiation	

2. Strip Chart Recording

Sixteen channels of analog data were also recorded. The parameters recorded are listed in Table B-2.

Table B-2

FLIGHT SIMULATION PARAMETERS RECORDED ON STRIP CHARTS

	Parameter	Symbol	Unit	Range
1.	Range	R	nm	-0.5 to 4.5
2.	Vertical height	H	ft	0 to 1000
3.	Localizer deviation (positive to right of glide path)	LOC	dots	±2.5
4.	Glide slope deviation (positive above glide slope)	GS	dots	±2.5
5.	Vertical speed	H	ft/s	±2.5
6.	Indicated Airspeed	IAS	kt	50 to 250
7.	Ground Speed	GNS	kt	50 to 250
8.	RPM on No. 2 engine	N_1	%	10 to 110
9.	Vertical Height	(same as 2 above, repeated on strip chart 2)		
10.	Along-track wind component	W_x	kt	±50
11.	Cross-track wind component	W_y	kt	±50
12.	Vertical wind component	W_z	kt	±50
13.	Wind difference	ΔW	kt	±50
14.	Command airspeed	CMD IAS	kt	50 to 250
15.	Pitch attitude	θ	deg	-5 to +15
16.	Angle of attack	α	deg	0 to 15

3. Summary Data Printout

The data content and format of the summary data printout is illustrated in Figure 8 in Section II of the report. Table B-3 provides a brief description of each data entry on this printout.

Table B-3

DATA ENTRIES OF THE SUMMARY PRINTOUT

Entry		Description	Units
1.	DATE	Calendar day, month, and year, each separated by a dash	day, mo, yr
2.	SUBJECT	Subject pilot, entered via the control box at the instructor's station	integer
3.	V(REF)	Reference airspeed, sampled at 800 ft GS altitude (1.3 V_S, with V_S a function of weight and flap setting)	knots
4.	TIME	Clock time at run initiation, using hours, minutes, and seconds	hr, min, s
5.	DISPLAY	Identifies test display, entered via the control box at the instructor's station	integer
6.	V(APP)	Target approach airspeed, as selected by the pilot; sampled at 800 ft GS altitude (V_{REF} + additives)	knots
7.	RUN NO	The master run number, entered via the control box at the instructor's station	integer
8.	WIND PRO	Identifies the selected wind profile, entered via the control box at the instructor's station	integer
9.	GNS (REF)	Reference ground speed, sampled at 800 ft GS altitude. $GNS_{REF} = V_{REF} + W_{x20}$, where W_{x20} is the X-component of wind at 20 ft height above runway in ground-axis coordinates--i.e., head winds have negative signs; for a tail wind, GNS_{REF} is greater than V_{REF}	knots
10.	RUN VA	Run validity, with 0 indicating an invalid run	integer

Table B-3
(Continued)

Entry		Description	Units
11.	GS ALT	Glideslope altitude (-X tan 3^{o})	ft
12.	DIST	Aircraft's along-track position	nm
13.	VERT OFFSET	Aircraft's vertical displacement from the glide path (positive above glidepath)	ft
14.	LAT OFFSET	Aircraft's lateral displacement from the extended runway center-line	ft
15.	VERT SPEED	Vertical speed	ft/min
16.	LAT SPEED	Ground-referenced cross-track velocity	ft/min
17.	GROUND SPEED	Ground speed, as displayed	kt
18.	AIRSPEED	Indicated airspeed	kt
19.	SI	Success index, with 1 indicating aircraft is within flight path offset and velocity limits, and 0 indicating outside limits	integer
20.	GS DEV	Mean and standard deviation (SD) of glide slope deviation over the 800-to-100-foot segment	dots
21.	LOC DEV	Mean and standard deviation of localizer deviation over same segment	dots
22.	AIRSPEED DROP	Mean and maximum airspeed drop below target approach airspeed over same segment	kt
23.	GROUND SPEED DROP	Mean and maximum ground speed drop below minimum preplanned ground speed, over same segment	kt
24.	FPA	Mean and standard deviation of flight path angle, over same segment	degrees
25.	RMS VALUES	Root-mean-square values of designated parameters over the 800-to-100-foot segment	as shown

Table B-3
(Concluded)

Entry		Description	Units
	a. VERT OFFSET	Same as Item 15	
	b. LAT OFFSET	Same as Item 16	
	c. PITCH STEERING	Pitch steering command bar displacement, in bar widths (BW)	
	d. ROLL STEERING	Roll steering command bar displacement, in bar widths (BW)	
	e. ELEVATOR ANGLE	Elevator displacements from faired (0 degree) position	
	f. AILERON ANGLE	Aileron displacements from faired position	
26.	GO AROUND	Pilot initiates go-around and depresses TAKE-OFF/GO AROUND button, at designated range and height	
27.	GO AROUND DECISION	Range and height at which pilot announces that he would initiate go-around	

Appendix C

PILOT BRIEFINGS AND DESCRIPTIONS

1. Initial Briefing

The purpose of the initial briefing was to introduce the objectives, method, and procedures to the subject pilots. Most pilots had flown the DC-10, but expressed a wide range of preferences for different cockpit callouts. The pilots were briefed just before their first-day runs. When two pilots were on-site at one time, the initial briefing was presented to both at the same time. An outline of the content of this briefing is given in Table C-1.

As shown in the outline, the initial briefing covered program objectives, the characteristics of the simulated aircraft, the airport and approach, aircraft configuration, and approach and go-around procedures. The methods of data collection were also discussed, with samples of the workload rating car (Figure C-1) and pilot acceptance form (Figure C-2) presented for examination and familiarization.

The initial briefing ordinarily took about 30 to 45 minutes and was concluded with the answering of pilot questions and a review of the schedule for simulator sessions and subsequent briefings and debriefings. Subject pilots were then asked to complete the Experience History form (Figure C-3). Immediately following the initial briefing, the pilot who was to fly the first simulator session was given a briefing on the particular test display and scheduled for the first run series.

2. Run Series Briefing

The run series briefing was normally given by the test director alone, although other persons were sometimes present. The purpose of the run series briefing was to insure that the pilot understood the display to be used in the ensuing run series and how it was to be used. Briefings for the baseline series were shortest, ordinarily less than 5 minutes, because of the use of standard displays and techniques. A review of approach procedures was normally all that was required for baseline. For other displays, notably ground speed wind difference and

RUN______

Place a mark along this line to indicate your subjective impression of the level of effort (physical and mental) that you applied to the approach you just completed. Don't worry about what effort means, or how the line might be scaled, or how much effort you applied to any other run. Just put the mark where you think it seems right to indicate lower levels of effort nearer the left end of the line and relatively greater levels of effort nearer the right end.

|———————————————————————|

Figure C-1. FORM FOR OBTAINING PILOT ESTIMATES OF WORKLOAD ON EACH SIMULATION RUN

Pilot ______________

Session ______________

Pilot Acceptance Rating

Based on the run series you just completed, and considering the cockpit instruments available and the manner in which you were briefed to conduct the approach, how confident would you feel about your ability to cope with actual low-level wind shear encounters like the ones you saw in the simulation?

______ 1. Not at all confident, I wouldn't want to have to rely on the technique used.

______ 2. Uncertain, I'm not sure the technique would be effective.

______ 3. Somewhat confident, I think I could manage some of the shears.

______ 4. Confident, I could manage most of the shear conditions.

______ 5. Highly confident, the technique I used would definitely be effective and I'm sure I could cope successfully with any of the shear conditions.

Figure C-2. FORM FOR OBTAINING PILOT ACCEPTANCE RATINGS FOR EACH EXPERIMENTAL AIDING CONCEPT

EXPERIENCE HISTORY

Name ______________________ Organization ______________________

Total PIC Time ______________ DC-10 Time ______________

Time last 90 days ____________ DC-10 last 90 days ____________

In your flying experience, have you ever encountered a Wind Shear which caused you to break off an approach? Yes______ No______ If yes: Please describe the circumstances:

Have you previously participated in any simulator studies of Wind Shear? Yes________ No_______ If so, where and when?

Have you flown an aircraft or simulator with displays of:

	Yes	No
Flight Path Angle?	______	______
Ground Speed?	______	______
Wind Difference	______	______

FIGURE C-3. FORM FOR OBTAINING SUBJECT PILOT EXPERIENCE HISTORY

flight path angle, longer briefings up to 15-20 minutes were required. Every effort was made to insure that the pilot understood how the display worked and how he was to use it in the shear environment.

3. Run Series Debriefings

Immediately following each series of simulator runs, each pilot was asked a series of debriefing questions about the display he had just flown. The debriefing was conducted by the test director, although other persons were often present.

A standard set of questions (see Table C-7) was used to elicit at least minimal information on each topic. In addition, pilots were encouraged to make comments on any aspect of the study, and the test director asked additional questions to clarify or expand on significant issues. The pilot acceptance rating form (Figure C-2) was filled out by the pilot at the end of each debriefing session.

All debriefings were recorded full-length on a cassette tape recorder for later extraction of significant comments.

4. Overall Debriefing

Following the final run series debriefing at the end of a pilot's participation in a particular experiment, an overall debriefing was conducted to cover the entire experiment and all run series. Perhaps the most significant information derived from the overall debriefing was the pilot's rank ordering of the experimental aiding concepts he had flown. The rank order was obtained by asking: "Which of the aiding concepts did you like best? Which would be next best?" and so on until all conditions had been ordered. Most pilots had little hesitancy about naming their first choice; lower-ranked items seemed to be harder to rank.

A number of the pilot subjects had participated either in Phase 1 or in more than one experiment of Phase 2. These pilots frequently made debriefing comments with reference to displays seen in earlier partic-

ipation, indicating that their responses may have been affected by such earlier exposure. Pilots were also asked about the quality of the simulation.

Overall debriefings were also conducted by the test director, but the first officer and simulation engineer were always present, and other test personnel frequently attended and participated. These debriefings typically lasted about 20-30 minutes, but were sometimes shorter because they came at the end of the day.

Table C-1

OUTLINE FOR INITIAL BRIEFING

I. Introduce participants

Normally Nice, Stephens, McTee

II. Program Objectives

A. To determine pilot and aircraft response to low-level wind shear.

B. To examine the benefits of some additional display information for detecting and combatting wind shear.

C. Subjects role in the project.

It is the aiding concept being evaluated and not the individual's skill & proficiency.

III. Study Operations

A. Airplane/simulator

(1) DC-10
(2) 350,000 lb.
(3) Visual system (Redifon)

B. Crew Procedures

(1) Standard airline operating procedures.
(2) First Officer will provide landing information card.
   a. Full Flap V ref 137 kts
   b. 22^{o} flap minimum maneuver speed 159 kts
   c. Use your normal add-ons.
   d. Announce your target speed (FO will set).

(3) Subject pilot executes hand flown flight director approach through to landing or go-around.

(4) FO will handle

   a. Gear
   b. Flaps/spoilers
   c. Communications
   d. Call-outs as requested by subject pilot. (Probably at least the following.)

      1. Glide slope active.
      2. Approach and passage of outer marker.
      3. Completion of final landing check.
      4. Altitude, airspeed and rate of descent as requested by the individual subject.
      5. Approaching and reaching minimums.
      6. Lights and runway sightings.
      7. Missed approach points.

Table C-1 (cont'd)

(5) Pilot announces go-around.

a. Applies thrust.
b. Establishes go around pitch attitude.
c. Calls flaps 22°.
d. Observes positive rate of climb.
e. Calls gear up.

C. Approach configuration

(1) Manual Flight Director approaches.

a. Begin 2 miles outside of marker.

1. 170 kts.
2. 22° flaps.
3. Gear up.

b. Gear down with glide slope.
c. Final flaps 35° or 50° at outer marker.
d. Roll out until simulator reset, normally at nose wheel touch down.

(2) Go-around procedure

a. Announce "Go Around".
b. Actuate Takeoff/Go-Around button on throttles.
c. Add thrust and 15° climb attitude.
d. Call for 22° flap and gear up when appropriate.
e. Climb straight ahead.
f. Expect freeze and reset early in climb.

D. Data Collection

(1) Emphasis on pilot-provided information

a. Ratings.

1. Work load.
2. Acceptance rating.

b. Questionnaires.
c. Comments.
d. Debriefings.

1. Series.
2. Post-experience.

(2) Recorded Data.

IV. Schedules

A. Simulator operation.

(1) 0900-1630 hrs.
(2) Briefing daily 0830 hrs.

B. Run Series.

(1) Simulator for 12 approaches 1:30 twice each day.
(2) Brief-debrief and free time.

Table C-2

BRIEFING ON USE OF GROUND SPEED DISPLAY

I. Background for concept.

A. Normal uses of ground speed pilots are familiar with--

(1) Flight planning
(2) Position reports
(3) Duration of flight
(4) Fuel consumption

B. Normal flight planning for approach speeds.

(1) Reference speed

a. Flap configuration
b. Gross weight
c. Built in 30% cushion over stall.

(2) Pilot applied add-ons.

a. 1/2 the steady wind
b. All of the gust factor
c. Maximum 15 kts.

C. Point out how above "conservative" plans have failed because of low level wind shear.

(1) At present shears not easily detectable in cockpit.
(2) Examples of failure of present system.

a. Kennedy Eastern Airlines Flight 66
b. Boston's Iberia

D. Failures brought on this study.

II. Basis for Concept

A. Review of ground speed

(1) Rate of motion over ground
(2) Result of interaction between true air speed and wind speed.
(3) Cockpit read-out of ground speed then allows a possible means of detecting and combatting shear.

a. Compare present true airspeed to present ground speed GNS to get reading on wind at present position.

1. TAS = GNS = calm wind
2. TAS greater than GNS = Headwind
3. TAS less than GNS = Tailwind

Table C-2 (Cont'd)

b. Comparison of wind aloft with reported surface wind.

1. Allows detection of possible shear.
2. Magnitude assessed by difference in velocity of wind aloft and on surface.

III. Cockpit presentation of ground speed. (Picture of diagram).

A. Green pointer on air speed indicator (Biased out of sight for GNS 2).

B. Green bug on airspeed indicator. (Only for GNS 1)

C. Digital readout (Covered up for GNS 1).

D. Five second delay.

IV. Method for Use

A. Computation of minimum preplanned ground speed (green bug setting).

(1) Convert V_{ref} +5 to TAS
(2) Subtract surface headwind component.

B1. Approach technique (GNS 1)

(1) Green bug set to minimum preplanned ground speed GNS_{ref}
(2) Indicated airspeed managed to keep green pointer at or above green bug.
(3) Use GNS_{ref} as additional minimum speed - keep IAS at or above pilot-selected target approach speed, as usual. (In case of head winds, V_{app} may go considerably above normal approach and landing reference speeds).
(4) Be aware of tailwinds.

a. Green pointer above IAS pointer when maintaining V_{app} shows tailwind component.
b. Tailwind component too high at too low an altitude go around.
c. In this case will fly V_{app} and V_{ref} as governing speeds (see example card).

B2. Approach technique (GNS 2)

(1) Green ground speed pointer and movable green bug do not appear.

Table C-2 (cont'd)

(2) Landing card prepared same as before.
(3) Pilot sets his speed bugs as desired.
(4) Manages approach to keep digital readout equal to or above GNS ref.
(5) Be aware of tailwinds.

a. Ground speed digital readout greater than TAS shows tailwind component.
b. Tailwind component too high at too low altitude-go around.
c. In this case normal V approach and V_{ref} will be governing speeds.

V. Conclusion - Salient points,

A. Ground speed in given airmass slow to change- mass of airplane itself must be accelerated or decelerated.

B. Air speed may change abruptly when wind shear occurs.

C. This technique should --

(1) Furnish pilot with sufficient energy (speed) to compensate for wind shear airspeed losses.
(2) Alert pilot to possible tailwind conditions.

D. Re-emphasize --

(1) Importance of following the prescribed airspeed management procedure.
(2) Focus of evaluation is --

a. Aiding concept.
b. Not individual skill and proficiency.

Table C-3

BRIEFING FOR WIND DIFFERENCE DISPLAY

I. Background for Concept.

A. To cope with wind shear pilot needs to know --

(1) That a shear exists -- detection.
(2) Magnitude of the shear.

B. Wind difference display furnishes the needed information.

(1) Computes the difference between the surface wind runway component and wind component at aircrafts present altitude.

(a) Difference only and not surface winds or winds at altitute.
(b) Values shown accurately represent magnitude of shear to be expected.
(c) To change values shown the aircraft must change its position and encounter changing winds or the surface wind must change.
(d) Because of this above characteristic, the display must be closely monitored.
(e) Gives continuously computed comparison.

II. Cockpit presentation of wind difference (show diagram or picture).

A. Digital read out below air speed indicator.

(1) ________ shows headwind component will increase 15 kts between present position and runway. (Comparatively lower headwind component on ground).
(2) ________ shows headwind component will decrease 15 kts between present position and runway. (Comparatively lower headwind component on ground).

B. Command airspeed bug.

(1) Activated at outer marker.
(2) Δ W negative -- shows speed to be flown to add full pad to V ref.
(3) Δ W positive or goes from negative to positive speed command bug won't go below selected target approach speed (V ref plus normal additives).

C. Fast-slow pointer on A.D.I.

(1) Indicates speed error between IAS and IAS command bug.
(2) IAS positive above command induces upward deflection of the pointer (fast).
(3) IAS below command displaces it downward (slow).

Table C-3 (cont'd)

III. Method for Use

A. Important that wind difference is monitored closely through entire approach, can reverse.

(1) When Δ W readings the positive throughout approach, airspeed control is normal using standard V approach and V ref speeds.

(2) When Δ W readings the negative, approach is made by adding full value of Δ W to V ref speed and maintaining it.

B. Approach Technique.

(1) Prior to start pilot checks landing card, announces target approach speed and sets command speed bug to this value.

(2) Individual movable bugs wet on airspeed indicator in normal fashion as subject desires.

(3) Starting approach fly normal 22^{o} approach flap minimum speed.

(4) As approach proceeds to outer marker monitor Λ W reading for indication of type of shear to be expected and to anticipate what the command speed bug will be calling for.

(5) After passage of outer marker and selection of landing flaps fly command speed bug.

(a) If Δ W negative, command speed is V_{ref} plug full negative pad or V_{app} whichever is greater.

(b) If Δ W is positive, command speed is V_{app}.

(6) Monitor fast/slow on ADI as check on proper speed.

(7) Monitor digital readout as speed check and trend guide.

Table C-4

BRIEFING FOR FLIGHT-PATH ANGLE DISPLAYS

I. General

A. Two computational algorithms for flight path angle (FPA):

1. Ground referenced (γ_{GM}) = Ratio of vertical speed to ground speed.

2. Hybrid-mixed computation (γ_H) = Ratio of vertical speed to airspeed.

3. Differences --

(a) γH reflects effects of longitudinal winds while γGM does not.
(b) γH shorter time constants -- expected to be more active in turbulence and more responsive to wind shear effects.

II. Use Concepts

A. Flight Director Approach -- Basically, thrust management based on FPA. Explain that short term indications may be misleading as to long term effects; e.g., headwind encounter: FPA shallows but pilot may not want to decrease thrust.

1. Capture glide slope and stabilize at V approach, tracking glide slope and localizer with Flight Director.

2. Monitor both airspeed and PFA throughout approach.

3. Manage thrust to maintain nominal -3° FPA.

(a) FPA gets steeper -- ADD thrust.
(b) FPA gets shallower -- monitor thrust over short term Called-for pitch down will help regain speed. Anticipate possible need to increase thrust in long term.

4. Monitor speeds for extremes -- 1. V approach
2. MAX flap speed

Summary - Expected to provide lead information to reduce excessive glide slop excursions and excessive decent rates.

B. Raw Data Approach -- Flight Director pitch bar biased out of view. Localizer tracked with Flight Director roll steering command bar. Vertical path controlled by changing pitch as called for by raw glide slope deviations and FPA readings.

1. Capture glide slope at outer marker by establishing FPA equal to published glide slop value.

Table C-4 (cont'd)

2. Maintain reference FPA using pitch control. Thrust management used simultaneously to maintain V approach.

3. Monitor raw data glide slope deviations and modify FPA to track glide slope.

   - Low on glide slope, shallow out FPA
   - High on glide slope, steepen FPA

4. Modify FPA 0.5° for each dot of glide slope deviation. Example: One dot high fly 3.5° FPA to interception.

5. On γ GM, return to -3° FPA and fly that; on γ H, modify FPA by "cut and try" and hold FPA that maintains -3° glide slope.

Table C-5

BRIEFING FOR MODIFIED FLIGHT DIRECTOR

General - (Deviations from previous general briefing)

1. Primary task is to try to follow Flight Director --

   Therefore:

   (a) Stay head down to 100'
   (b) Do your best to complete approach to 100'
   (c) Above 100' simply announce "Go Around", if that is the decision. Do not execute.
   (d) At 100' pilot goes visual and lands or goes around.

2. Runs start at 1500'

   (a) Final approach configuration

      (1) Full Flaps or Landing Flaps
      (2) Gear Down

   (b) Check lists complete
   (c) In trim, on glide slope, on localizer.

Table C-6

BRIEFING FOR USE OF WIND DIFFERENCE DISPLAY IN EXPERIMENT 3

I. Background and basis for concept.

A. Wind difference computed to show difference only between -

1. Surface wind along runway as reported by the tower.
2. Wind Component at aircrafts present altitude (based on computation of true airspeed and DME ground speed).

B. Wind difference is estimate of magnitude of possible shear between present position and surface.

1. Does not give value of either surface wind or wind at altitude.
2. To change the value the aircraft must change position and encounter changing winds or surface wind must change.

C. Wind difference could show -

1. Positive difference, that is, possibility of indicated airspeed increasing (increasing headwind or decreasing tail wind.

2. Negative difference, that is, possibility of indicated airspeed decreasing (decreasing headwind or increasing tail wind).

II. Cockpit presentation

A. No digital indication or readout. Wind difference Δ W reflected only on command speed bug.

B. Command speed bug will show -

1. Normal pilot selected target approach speed if wind meter calculations are positive (gain in air speed) or

2. Vref plus the full value of any negative wind difference calculations (loss in airspeed).

III. Use of Δ W - biased airspeed command.

A. Simply fly command air speed bug as usual -

1. If Δ W is a positive, command speed bug is pilot selected V approach.

2. If Δ W is a negative, command speed bug will reflect the full speed pad. (Note: command speed bug will be changing during approach as wind difference changes)

B. Fast/Slow on ADI may be used in normal fashion.

Table C-7

PILOT DEBRIEFING QUESTIONS

1. Did you consider the briefing and the training runs in the simulator to be an adequate preparation for the approach management task you were asked to perform?

2. How did you actually use the experimental display for managing airspeed?

3. Do you consider this technique to be an effective way of coping with low level wind shear?

4. Would it be practical in actual line operations?

5. Did you experience any difficulty with the way the information was displayed, i.e., with the location, with readability, or the interpretation of the display?

6. What suggestions do you have for improving the test display or the way it might be used?

7. (Pilot acceptance rating)

8. Did you have any problems or difficulties with the simulator (aircraft response, motion, visual, etc.) you'd like to comment on?

9. Any additional comments or suggestions? (Please feel free to offer any negative or critical comments regarding your experience with the test display or any other aspect of the study).

Appendix D

FLIGHT-PATH-ANGLE SURVEY

The following questionnaire was distributed to approximately twenty pilots who had participated in USAF studies of head-down Flight Path Angle displays (see text). Recipients were asked to answer on the basis of their actual flying experience.

FLIGHT-PATH-ANGLE USAGE QUESTIONNAIRE

1. Please describe your experience in flying flight path angle (FPA) displays:

   Aircraft type(s) ______________________________

   Total hours:

   __________ 100 or less
   __________ 100-500
   __________ 500-1000
   __________ over 1000

2. If you know it, please give the computation used for the FPA display. (It may be important to know whether accelerations were used in the computation)

3. a. What kind of instrument display of FPA did you use?

   b. Where on the panel was it located? (Sketch if you wish.)

   c. Did you consider this an appropriate and effective location?

   d. Could you suggest a better display? a better location?

4. How did you use the FPA display in approach and landing?

   __________ as a control instrument
   __________ as a performance instrument
   __________ as a combination
   __________ other (please describe)

5. Did you find FPA effective? If not, why not?

6. What other instruments did you cross-check against FPA?

7. Was the PFA indication stable?

8. How did you correlate FPA with glide slope when flying ILS?

9. On what kind of approach was FPA most beneficial?

10. Were there approaches on which FPA did not help? If so, please specify.

11. In what segment of the approach did FPA help most?

12. Were there portions of the approach where it did not help at all?

13. a. Do you regard FPA as a primary or as a supporting parameter?

    b. Why?

    c. If primary, what supporting displays are required?

    d. If supporting, which primary display(s) does FPA support?

14. What did FPA tell you about winds?

15. Did you ever think you encountered a wind shear while flying with FPA displayed? If so, please describe the circumstances and the instrument indication.

16. What is the main deficiency of FPA, in your flying experience?

17. What is its chief advantage?

Appendix E

FLIGHT PATH ANGLE COMPUTER MODEL STUDY

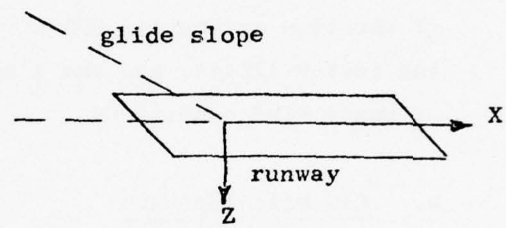
This paper summarizes the evaluation of FPA algorithms for use in the Phase 2 experiments in the Douglas Development Flight Simulator. The following recommendations are based on quantitative results obtained from simulation runs of the pitch-plane dynamics of the DC-10 on our ModComp computer.

Recommendations:

The following two FPA measures are recommended for testing in the Phase 2 experiments:

1. Ground Referenced

$$\gamma_{GM} = \frac{V_{HM}}{V_{XM}}$$



where

$$V_{HM} = \frac{-1}{1 + \tau_H S} Z$$

S = Laplace transform variable

$\dot{Z}$ = Rate of change of height above runway

τ_H = 2 seconds

$$V_{XM} = \frac{1}{1 + \tau_X S} \dot{X}$$

$\dot{X}$ = ground speed along runway

τ_X = 5 seconds

2. Mixed

$$\gamma_H = \frac{V_{HM}}{V_{AM}}$$

where

$$V_{HM} = \frac{-1}{1 + \tau_H S} \dot{Z}$$

τ_H = 2 seconds

$$V_{AM} = \frac{+1}{1 + \tau_A S} V_a$$

V_a = true airspeed

τ_A = 2 seconds

The following two use concepts are recommended for testing with both ground referenced and mixed FPA.

a. FD Coupled

Fly the pitch and roll steering bars on the flight director with manual throttle control. After stabilization of the approach with airspeed at V_{app}, use the pitch and roll steering bars as the primary pitch control and FPA as the primary throttle control. Decrease thrust when FPA is greater than the nominal -3^{o} glidepath (e.g., FPA = -2.5^{o}) and increase thrust when FPA is less than the nominal -3^{o} glidepath (e.g., FPA = -3.5^{o}). Adjust thrust as necessary to insure that airspeed remains above V_{ref} while not exceeding the maximum airspeed for the flap setting used. Note that a change in pitch will also change FPA. Large control deflections should therefore be accompanied by the usual amount of throttle movement. FPA will respond quickly to aircraft path following instabilities, and the display will become more active in turbulent or gusty wind conditions.

b. Raw Data Approach

Fly raw localizer and glide slope data using normal manual throttle control and airspeed management, using FPA to assist in pitch control. After stabilization of the approach on the nominal glidepath with airspeed at V_{app}, FPA is used to provide short term information for pitch control with the glide slope deviation providing, relative to FPA, longer term information for pitch control. The angle at which the aircraft is closing on (or departing from) the glidepath may be judged by looking at the FPA displacement from the nominal -3^{o} path angle. For example, if the aircraft were 1 dot glide slope deviation below the glide path and the FPA tape read -3^{o} (i.e., parallel to the glidepath), the aircraft would be required to pitch up until the FPA read at least -2.6^{o} in order to entercept at the GPIP. Although the value of $.4^{o}$ change in FPA per dot glide slope displacement is the minimum required, it is likely that in a typical smooth approach without wind shear the change in FPA required to correct a glide slope displacement will be less than 1^{o}. Larger deflections of FPA which do not appear to the pilot to be the direct result of a significant control input are probably due to wind shear. The main

effort should then be to counteract the shear. For example, consider the aircraft at 1 dot glide slope deviation above the glide slope which encounters a tailwind/downdraft wind shear. FPA reads -6°. The proper action is to pitch up (adding power if necessary) in order to satisfy FPA. Even though the aircraft is above path, the change in FPA required to correct the path without wind should be much less than that required to counteract the wind shear. FPA will respond quickly to aircraft path following instabilities, and the display will become more active in turbulent or gusty wind conditions.

Discussion of test results:

Various pitch and thrust control algorithms incorporating FPA correction terms were tested on a simplified model. The characteristics of the simulation system and the procedure used to generate the test runs may be summarized as follows:

- Implementation was performed on a general purpose digital computer with input of test conditions and control variables from keyboard and output in the form of graphic displays, plots and printed statistics.
- The equations of motion were restricted to the pitch plane, i.e., vertical and longitudinal translation and rotation about the pitch axis.
- The aircraft simulated was the DC-10.
- No pilots were used. Autocoupled approaches were flown with the pitch attitude control being typical of that provided by an autopilot and the thrust being either fixed or controlled by a separate algorithm based on maintaining a reference airspeed. The control laws were optimized to give good performance over all the test conditions. The "standard" pitch control algorithm contained the following feedback terms: pitch, pitch rate, vertical offset from glide slope. The standard thrust control algorithm contained airspeed as the feedback parameter.
- The pitch attitude and the thrust control laws were then each augmented with FPA. In each case an additional proportional amount of control effort was added based on maintaining a reference FPA.
- The test conditions included step and ramp shears in longitudinal and/or vertical wind versus time and the 5 wind profiles versus height to be used in the Phase 2 simulation. All runs were without turbulence.

- o Since no flare law was used, touchdown data was not used in the evaluation. Performance was judged on approach outcome and parameters calculated over the 700 ft. - 50 ft. glide slope height flight path segment.

In brief, the test results were consistent and, within the context of the control law strategy used, supported several generalizations. These generalizations are summarized below.

Comparative performance of the FPA measures:

Besides the ground-referenced and the mixed algorithms, the following air-mass referenced FPA was tested.

$$\gamma_a = \frac{1}{1 + \tau_a S}\{\theta - \alpha\}$$

θ = pitch angle
α = angle of attack
τ_a = time constant

Results for the thunderstorm wind profile which contains both longitudinal and vertical winds are summarized in Figure E-1. The graph shows glide slope tracking error measure MEA* plotted for several test

---

*MEA is the maneuver equation average, a measure of glide slope tracking error defined as the mean value of the function of f over the flight path segment where:

$$f = \begin{cases} |\Delta H + 3.5\ \Delta\dot{h} - 3.5\ \dot{\theta}| & \text{for } h \leq 180 \text{ ft} \\ \dfrac{16}{.089h}\ |\Delta H + 3.5\ \Delta\dot{h} - 3.5\ \dot{\theta}| & \text{for } h \geq 180 \text{ ft} \end{cases}$$

where

h = height above runway in ft
ΔH = vertical offset from glide slope in ft
$\Delta\dot{H}$ = rate of change of ΔH in ft/sec
$\dot{\theta}$ = rate of change of pitch angle in deg/sec

In general a smaller value of MEA will indicate better performance. References are:

1. "Inertially Augmented Approach Couplers - A Review of Previous Work," Collins Radio Group, Rockwell International, March 17, 1976 (for SRI 4364, contract DOT FA75WA-3650).

2. Bleeg, R. J., et al, "Inertially Augmented Automatic Landing System: Autopilot Performance with Imperfect ILS Beams", The Boeing Company, Report No. FAA-RD-72-22, April 1972.

conditions. Although only the MEA is shown, other performance criteria such as glide slope deviation, vertical speed, etc., were consistent with these results. Caution should be used when interpreting this figure. As a comparison, the performance between the run using standard pitch control with thrust control based on airspeed (run #1, Figure 1) and the run using ground referenced FPA augmentation in both pitch control and thrust control (run #4 in Figure 1) shows glide slope deviation and vertical speed error improved roughly by a factor of 2.

Control of both pitch attitude and thrust improved with the addition of ground referenced and mixed FPA. Performance with airmass referenced FPA varied in a manner depending on the particular wind profile used. In the case of winds consisting entirely of longitudinal components air-massed FPA showed an improvement in performance. However, in winds containing entirely vertical components the addition of air-massed FPA was detrimental to performance. Since the limitation of air mass referenced FPA in the presence of vertical winds prevents it from being used effectively, it is recommended that it not be tested in the Phase 2 piloted simulations. Based on their performance in the presence of moderate to severe windshears, the FPA measures were ranked as follows:

Algorithm	Pitch attitude control performance
Standard + γ_{GM}	Best overall
Standard + γ_H	A close second to Standard + γ_{GM}
Standard	Baseline
Standard + γ_a	Inadequate in the presence of vertical winds

Algorithm	Thrust control performance
Airspeed + γ_{GM}	Best overall
Airspeed + γ_H	Second to γ_H
Airspeed	Baseline, standard pitch control with thrust control based on airspeed yielded completely adequate performance over the inversion and frontal wind profiles.
Standard + γ_a	Inadequate in the presence of vertical winds.

Performance with the introduction of time delay:

As the appropriate time constants involved in the computation of FPA were lengthened, the performance benefit over the systems not using FPA decreased. The result for thrust control is illustrated in Figure E-2. From the graph it is apparent that for the thunderstorm wind profile the addition of γ_{GM} to the thrust control law does not improve performance for smoothing time constants of 5 seconds or more. Moreover, best performance is obtained with a minimal time constant. Similar results were obtained from the data pertaining to pitch attitude control.

In a piloted system the time constant will be limited by the pilot's ability to read the display. Since turbulence was not included in the simulation, the amount of smoothing necessary for the display was difficult to assess. However, past experience shows this to be on the order of seconds.

It is known that ground speed measurements may employ a longer time constant than that used for vertical speed. With the vertical speed time constant held at 2 seconds, the ground speed time constant was varied. Over the thunderstorm wind profile thrust control performance varied little even when ground speed time constants as long as 25 seconds were used. Performance then fell off when the ground speed time constant was extended beyond 30 seconds. The performance with a 2 second time constant on vertical speed and 25 seconds on ground speed was equivalent to the performance obtained with a 2.5 second time constant on both vertical speed and ground speed. Similar results were obtained for the pitch control system. For the purposes of the Phase 2 simulations, it is recommended that the time constant on ground speed be the same as that used on Experiment 1 (5 seconds).

Determination of FPA aiding concepts:

In summary, the data using autocoupled approach indicates that FPA (in particular γ_{GM} and γ_H) shows promise as an aid to coping with wind

shear. Potentially, FPA could be applied to any of several flight control modes for pitch attitude or thrust control during the landing operation. The flight control modes may be classified as being either coupled (or flight directed) systems, manually overridden coupled systems, or manually controlled systems. Although FPA could be incorporated directly into the coupled systems, this approach lies outside the time constraints for Phase 2. It was also considered impractical for the pilot to override either pitch steering bar commands or other coupled systems due to the problem of specifying rules for resolving the conflicting command displays. An analysis of each system involved would be required. It would be worthwhile to examine the above possibilities in the future.

Given the above constraints FPA can be used to augment pitch attitude control by fling raw glide slope deviation with FPA. Similarly for thrust control manual throttle would be used based on airspeed and FPA. The manual technique would be to maintain some reference flight path angle. That is, for pitch control, if FPA is less than (steeper than) the reference, pitch up, and if FPA is greater than (more shallow than) the reference, pitch down. For thrust control this becomes: if FPA is less than the reference, add thrust, and if FPA is greater than the reference, decrease thrust. Since γ_H contains small bias errors (due to ground speed being replaced by airspeed in the computation) small bias errors in a practical system should be ignored. The two recommended use concepts attempt to incorporate the above factors in a practical manner.

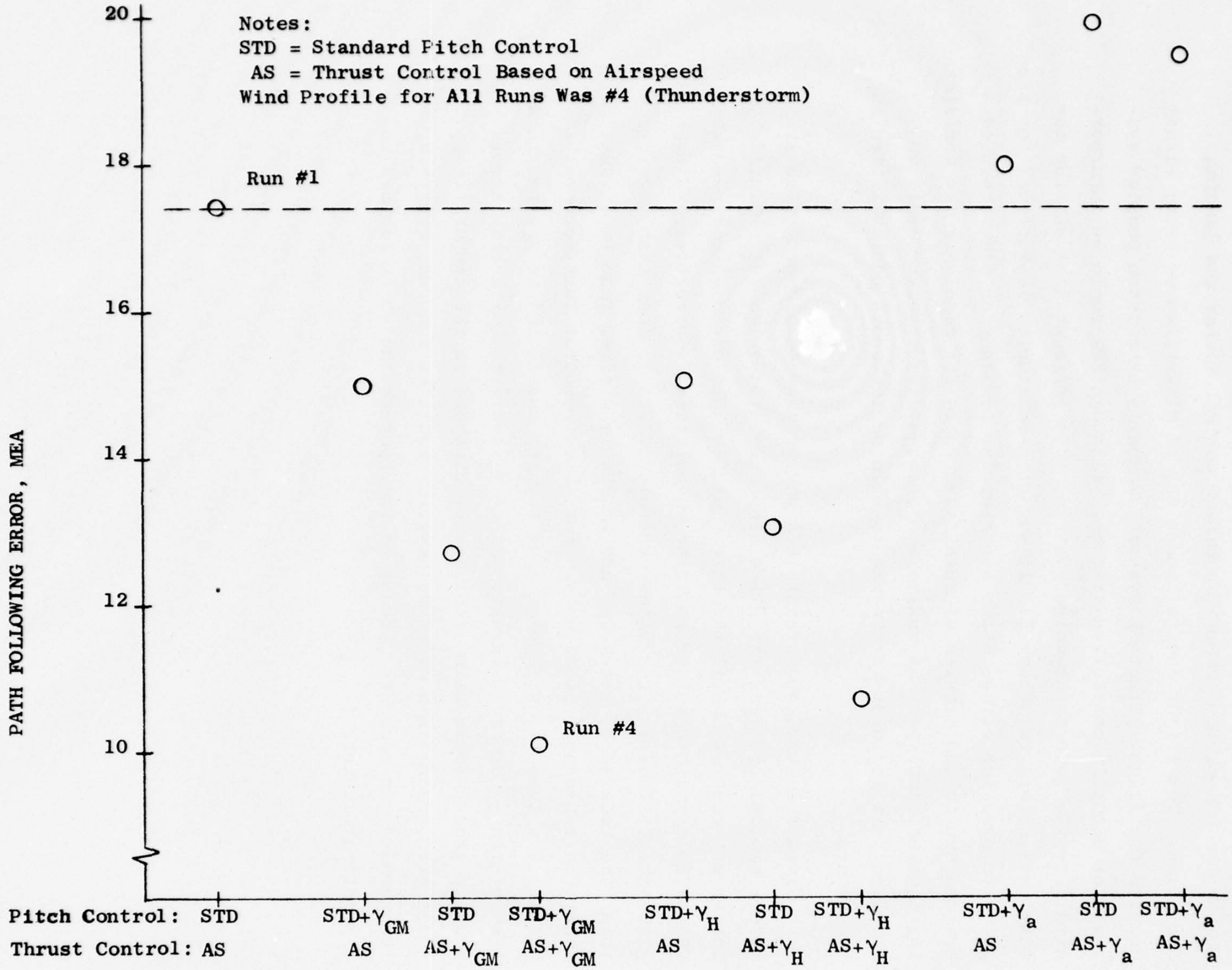


Figure E-1. COMPARISON OF PATH FOLLOWING ERRORS

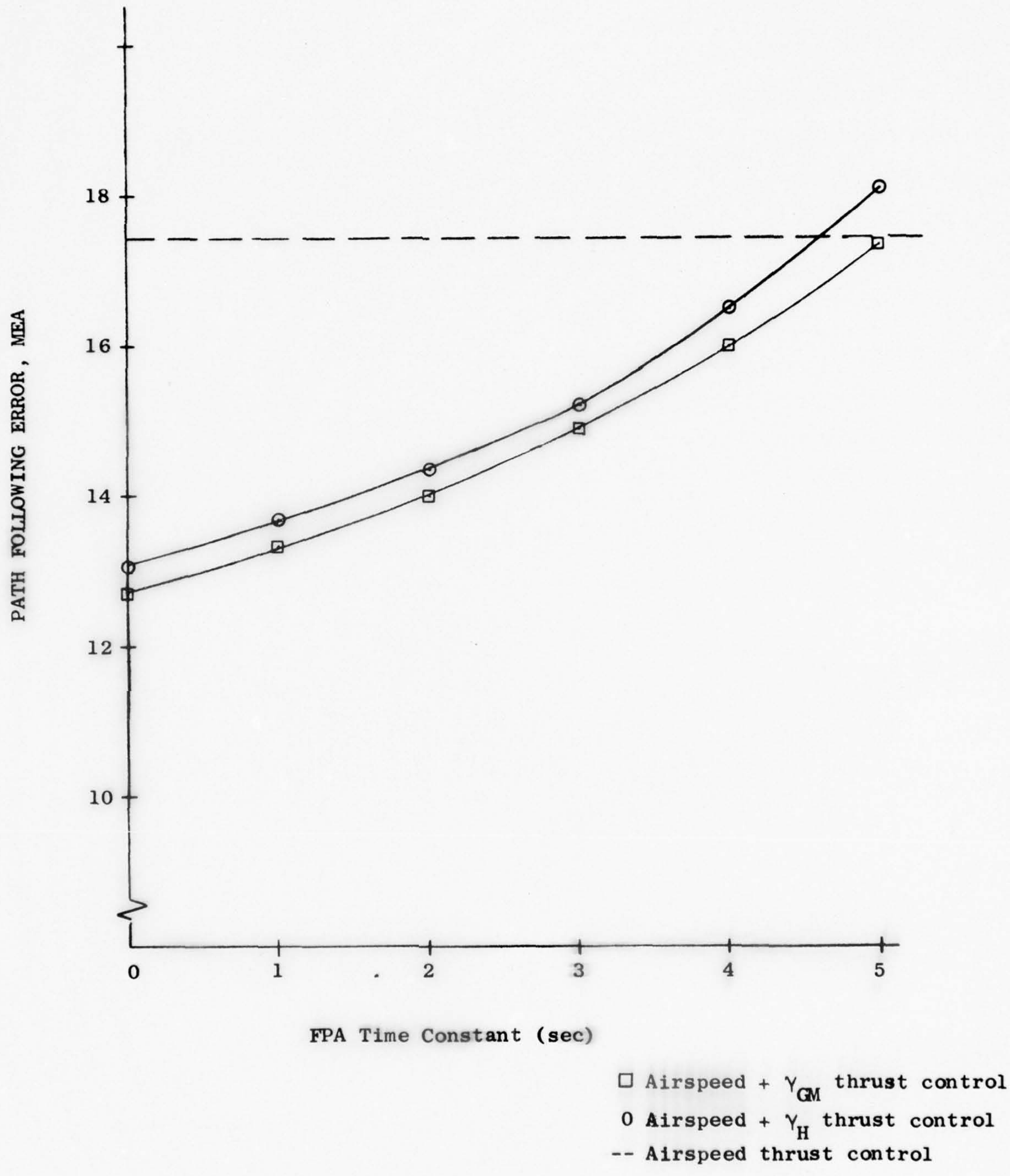
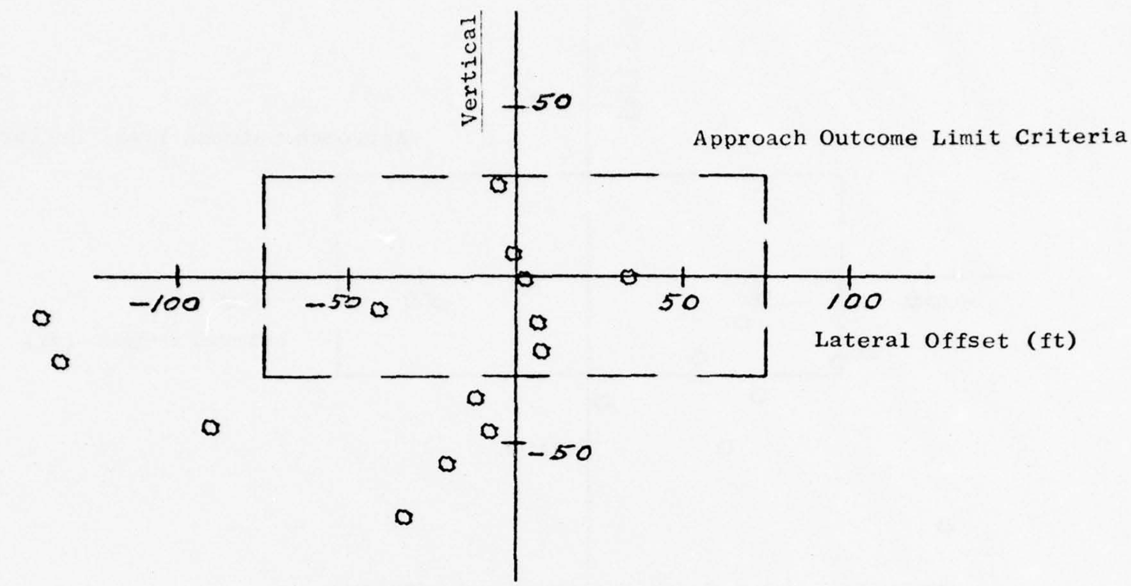


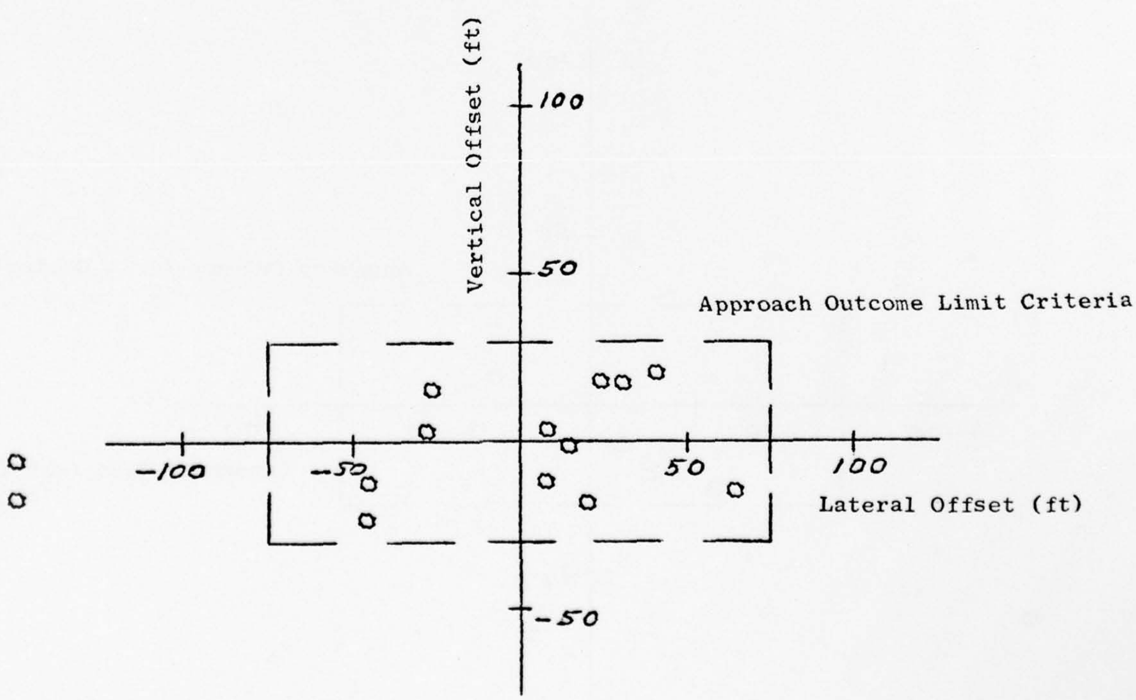
Figure E-2. ERROR LEVEL OF THRUST CONTROL VS. TIME CONSTANT ON FPA

Appendix F

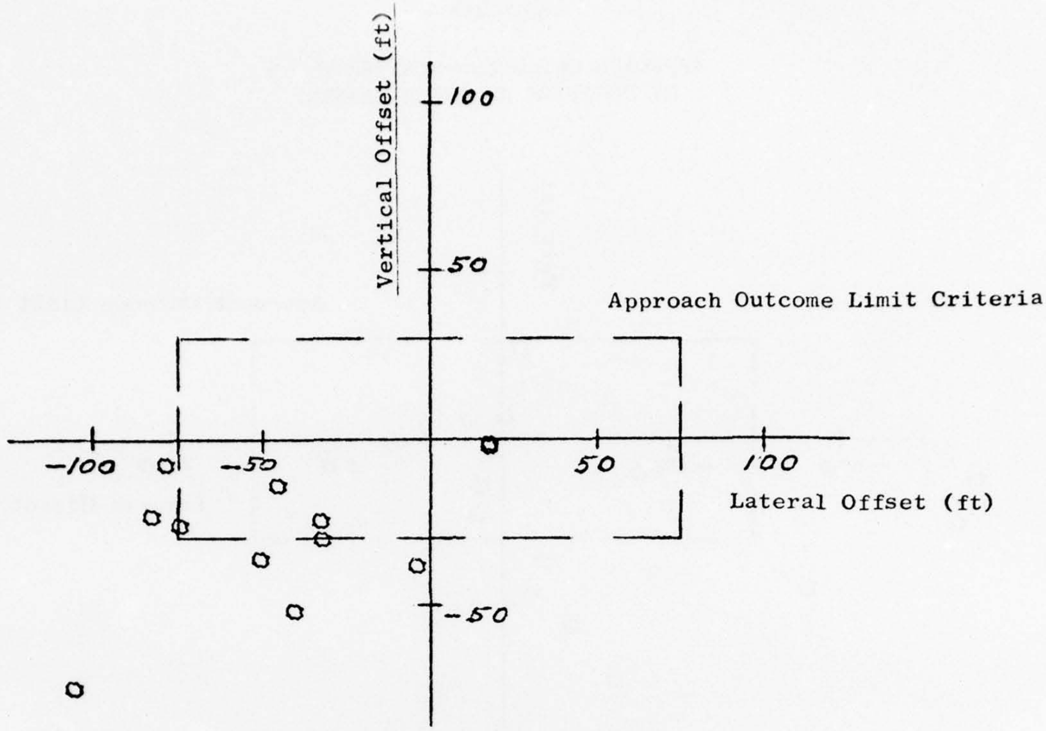
APPROACH OUTCOMES--SCATTER PLOTS
OF POSITION AT INNER MARKER



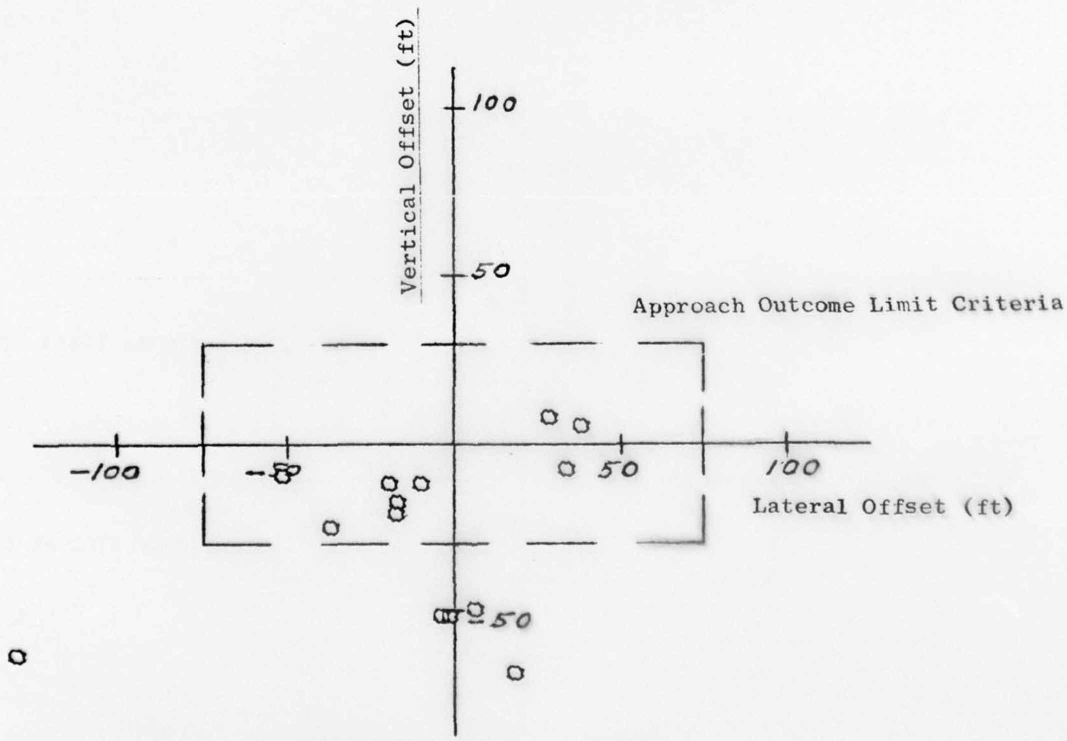
EXPT. #1 BASELINE FRONTAL



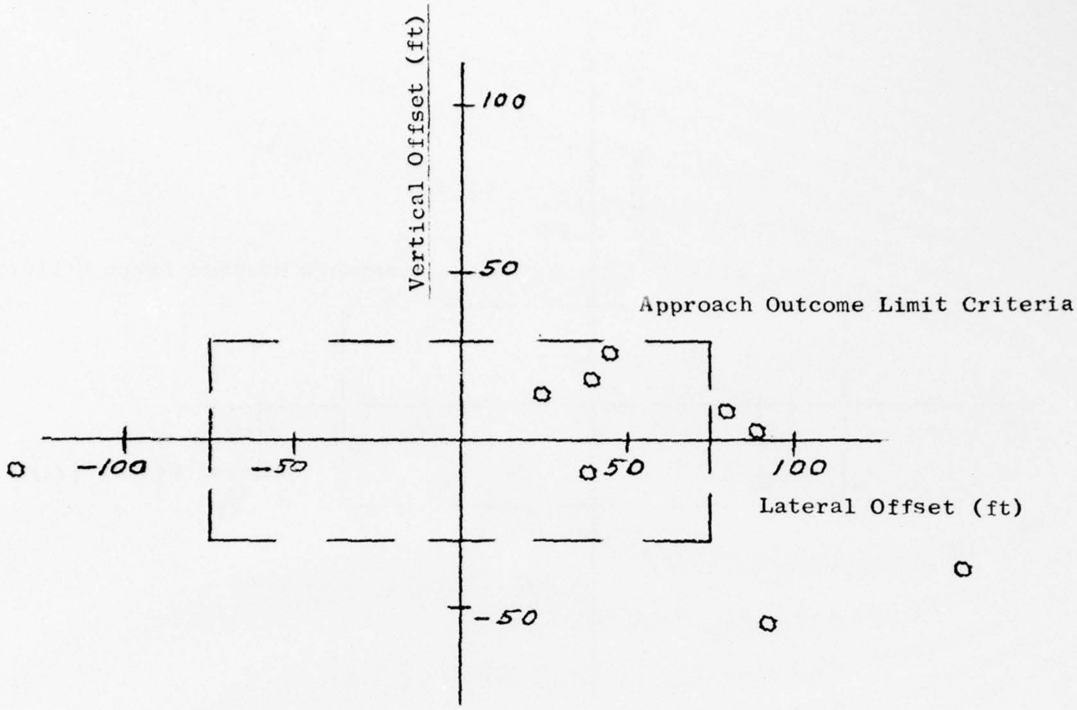
EXPT. #1 GNS-1 (Pointer display) FRONTAL



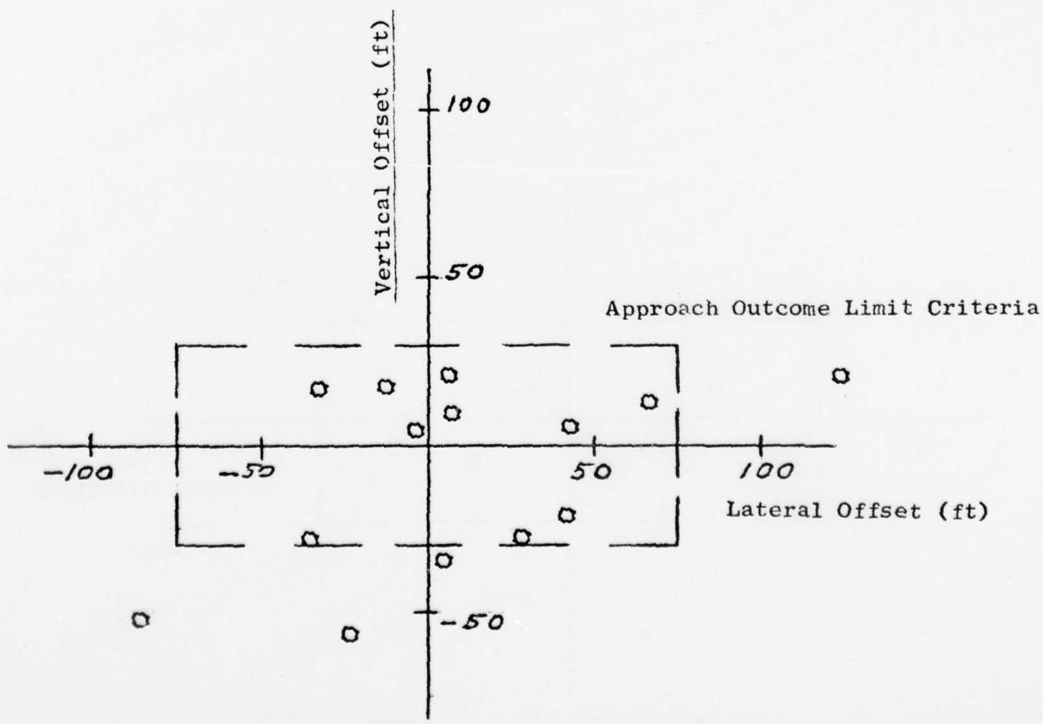
EXPT. #1 GNS-2 (Digital Readout) FRONTAL



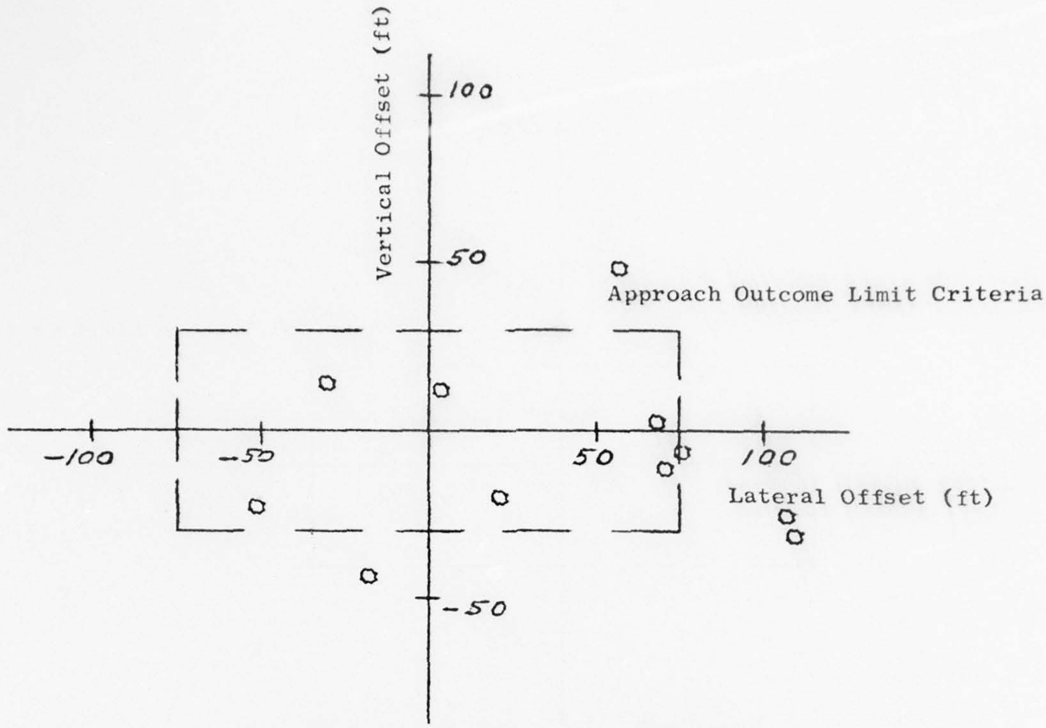
EXPT. #1 ΔW (Wind Differance) FRONTAL



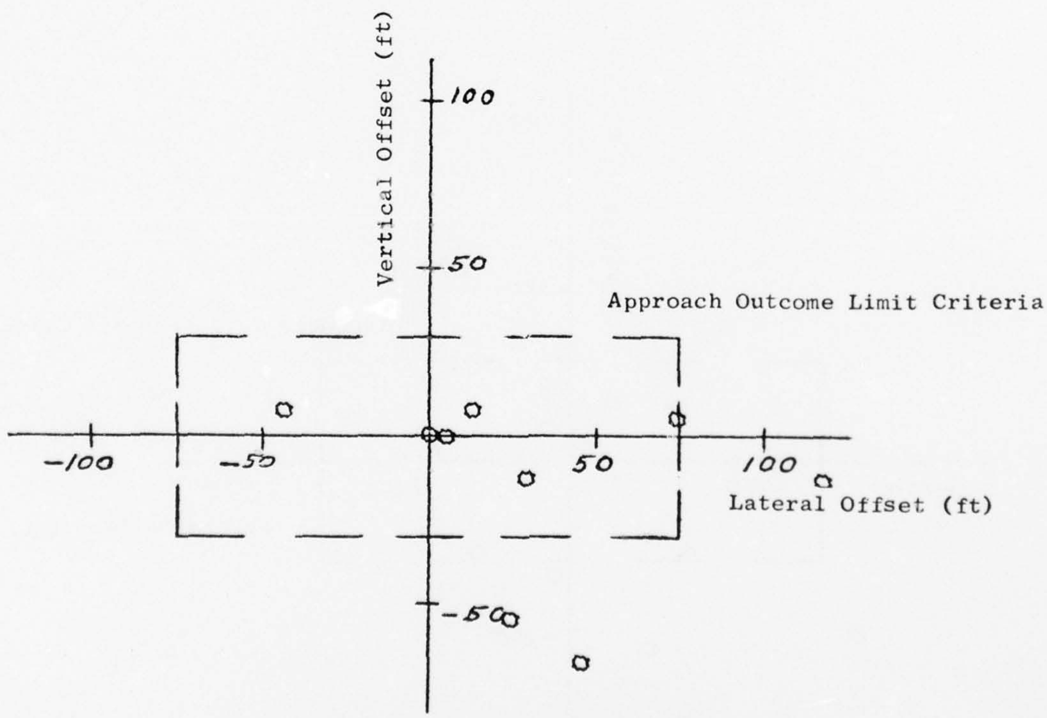
EXPT. #1 BASELINE THUNDERSTORM



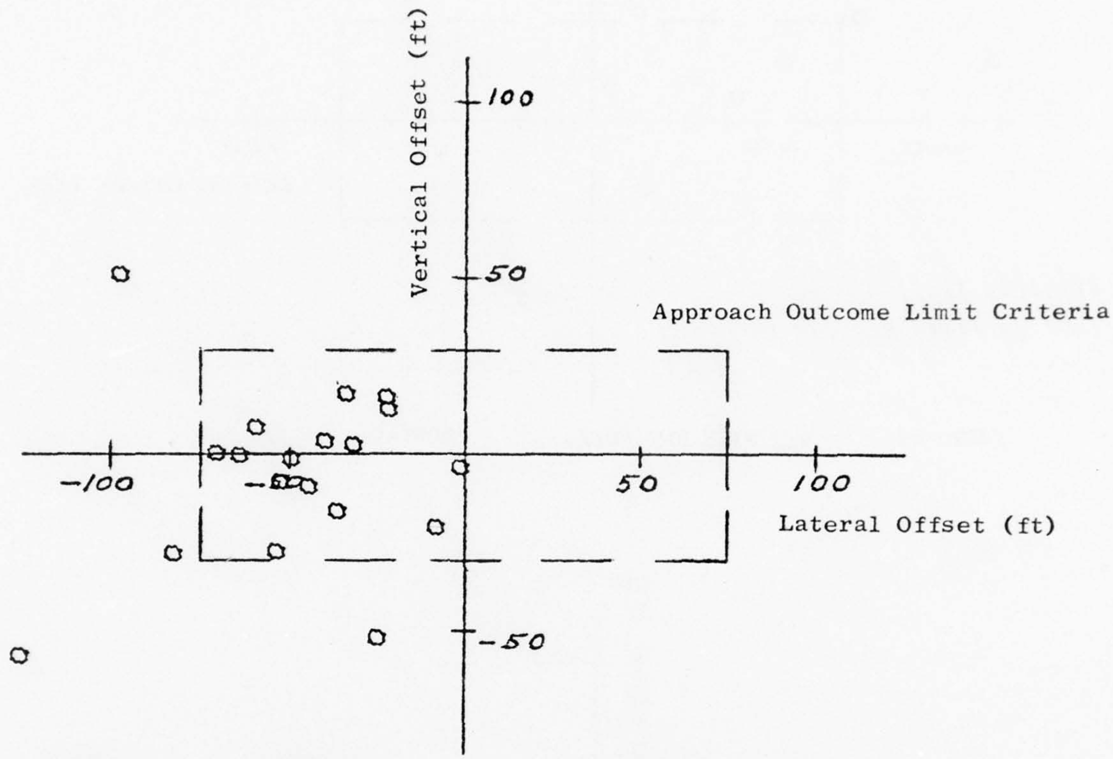
EXPT. #1 GNS-1 (Pointer display) THUNDERSTORM



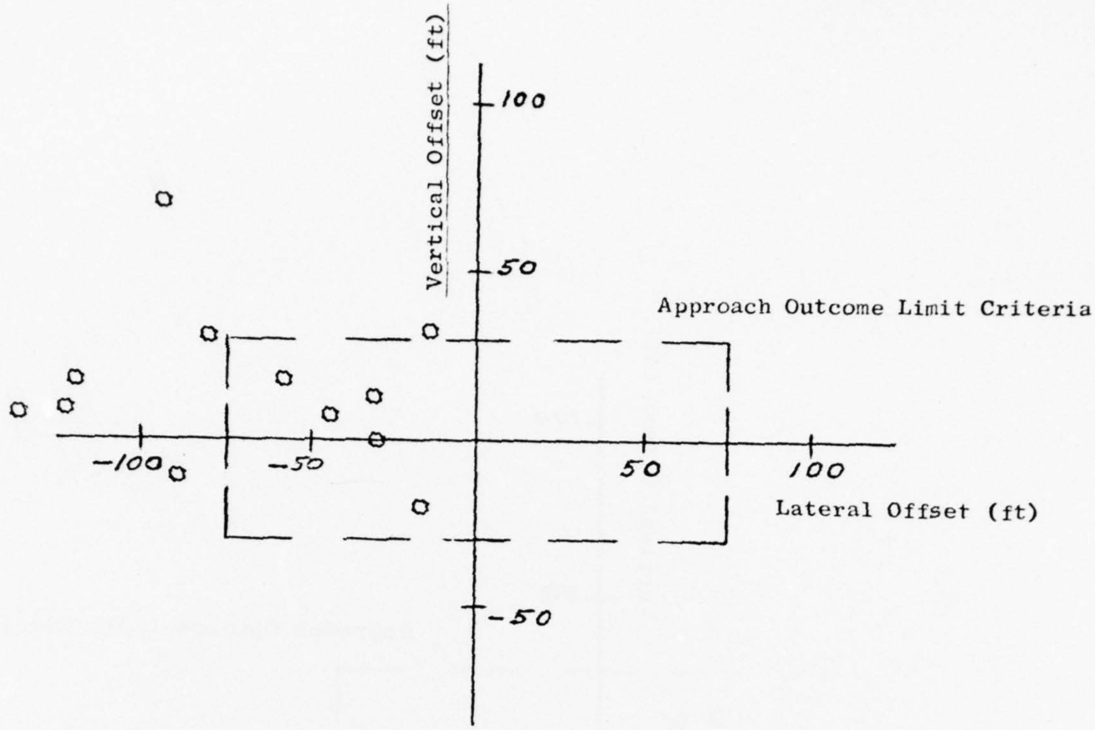
EXPT. #1 GNS-2 (Digital Readout) **THUNDERSTORM**



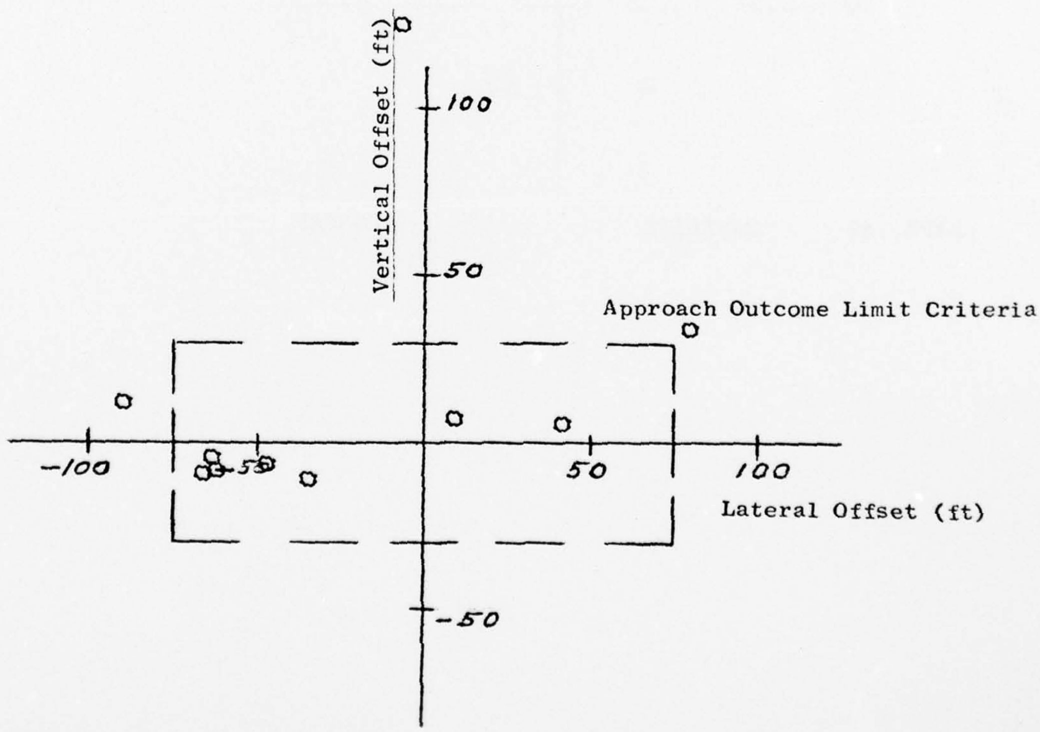
EXPT. #1 ΔW (Wind Differance) **THUNDERSTORM**



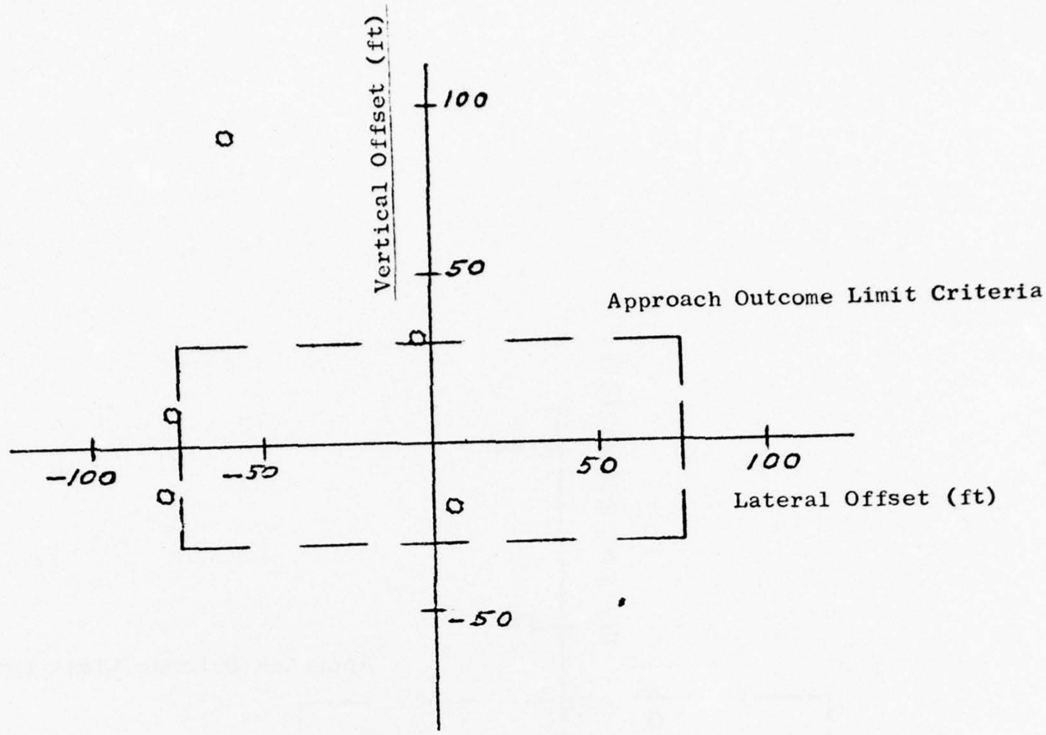
EXPT. #2 BASELINE FRONTAL



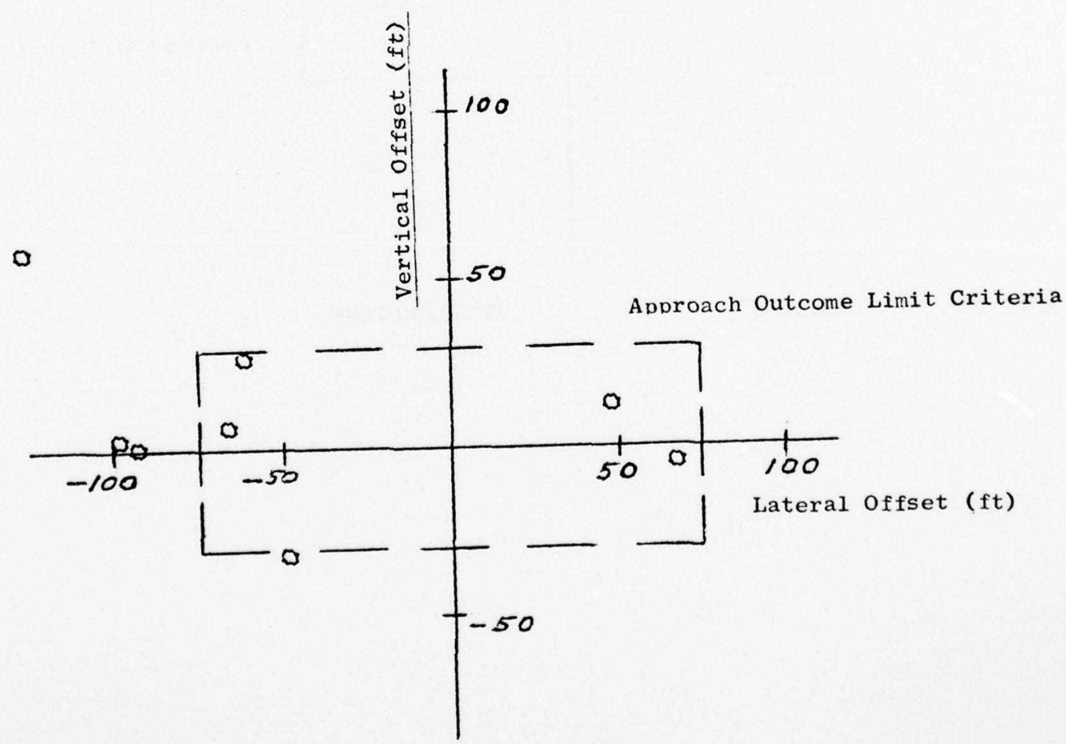
EXPT. #2 γ_{GM} WITH FLT. DIR. FRONTAL



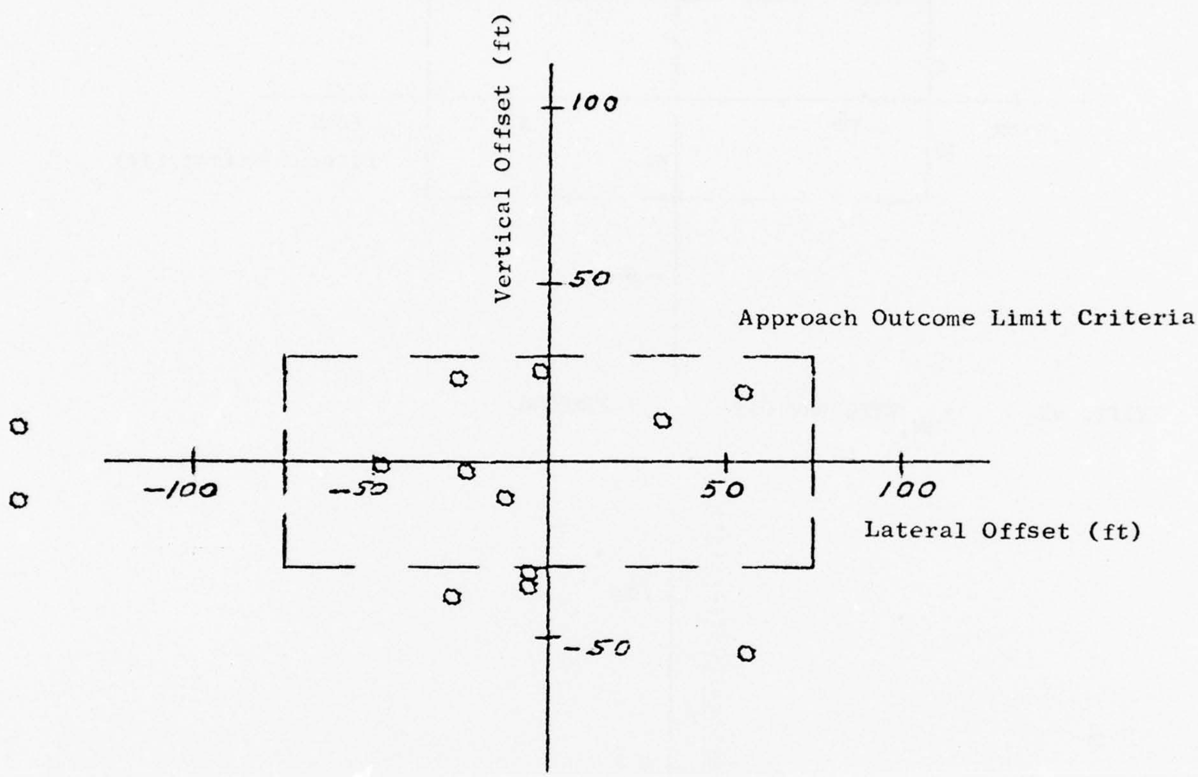
EXPT. #2 γ_H WITH FLT. DIR. FRONTAL



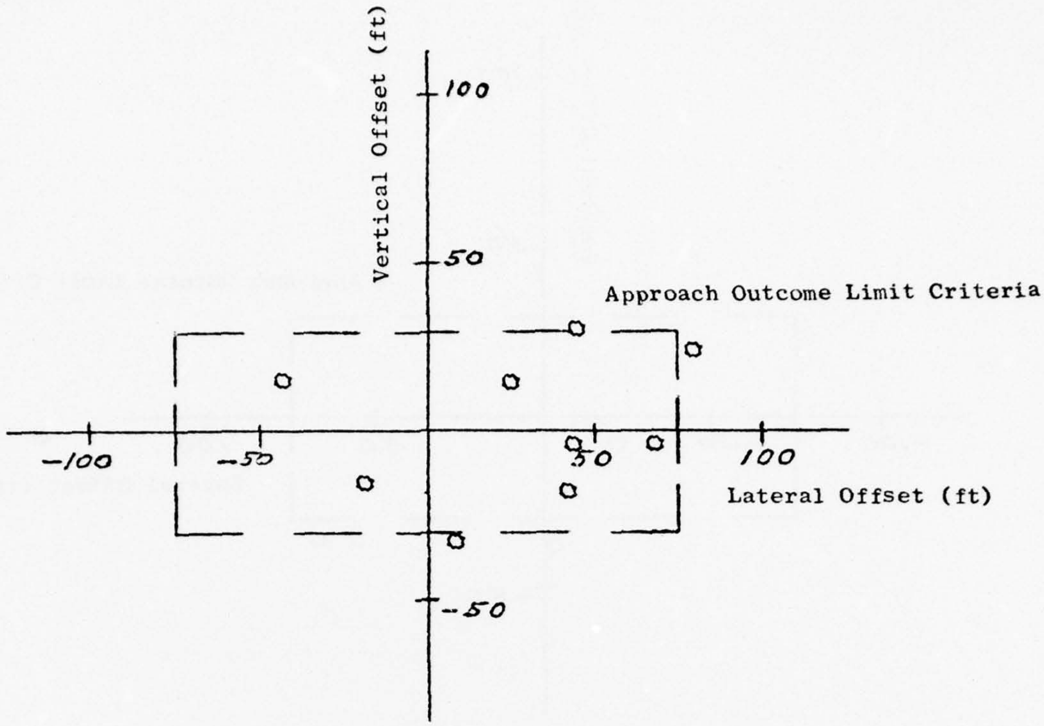
EXPT. #2 γ_{GM} WITH RAW DATA FRONTAL



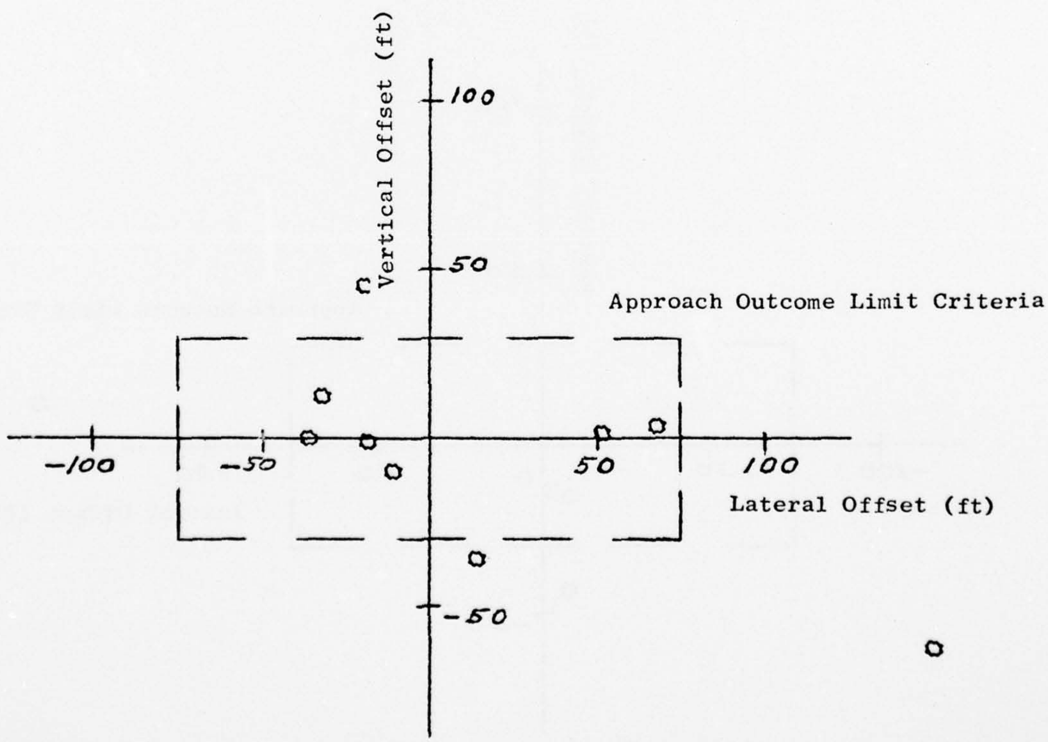
EXPT. #2 γ_H WITH RAW DATA FRONTAL



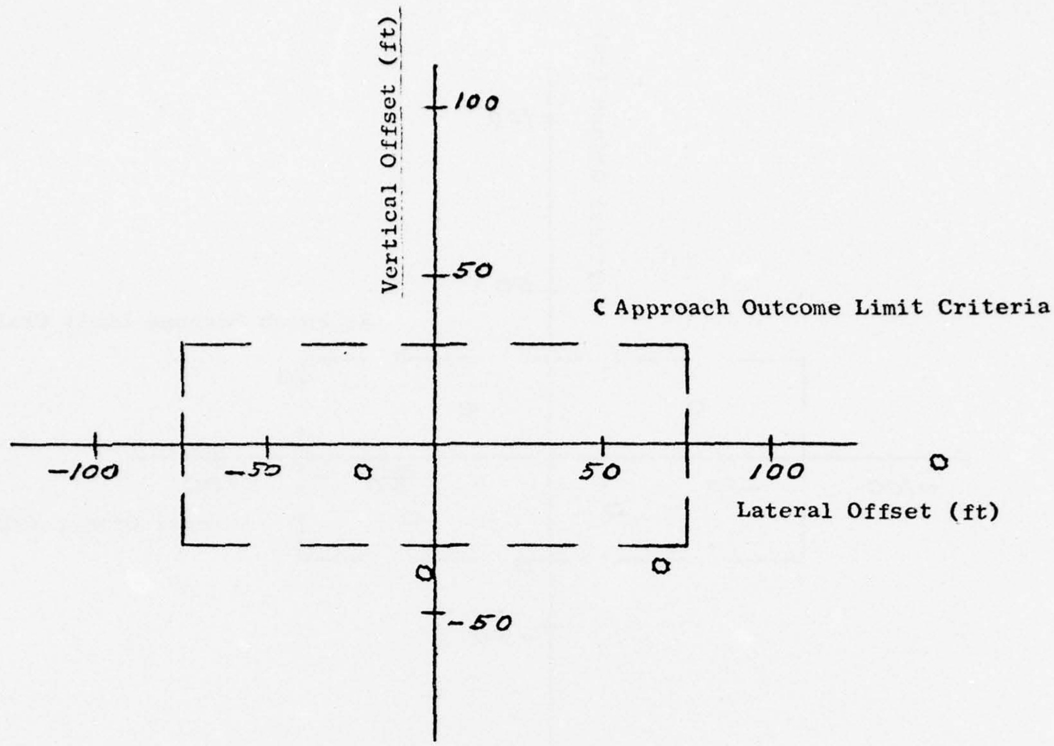
EXPT. #2 **BASELINE** **THUNDERSTORM**



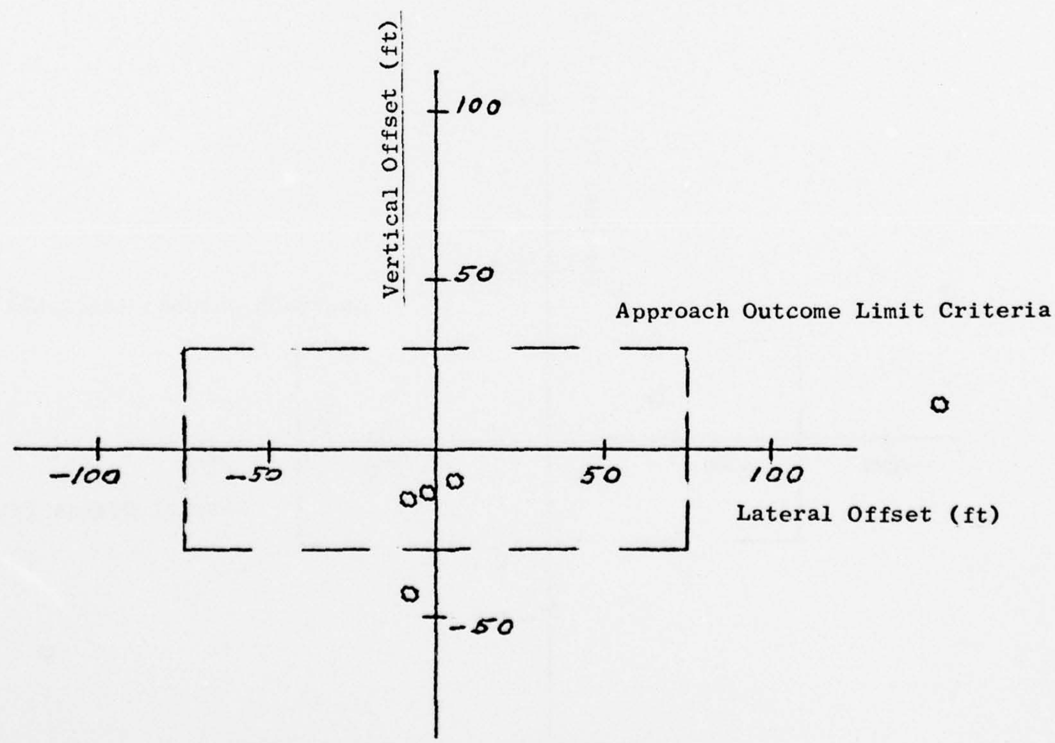
EXPT. #2 γ_{GM} WITH FLT. DIR. THUNDERSTORM



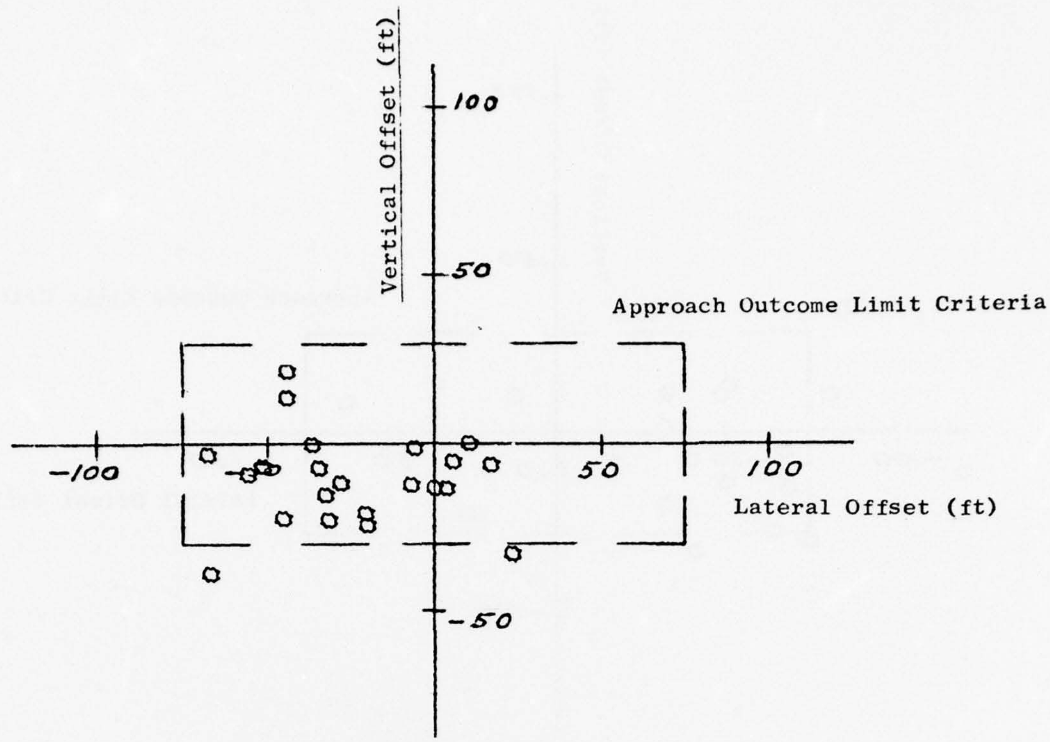
EXPT. #2 γ_H WITH FLT. DIR. THUNDERSTORM



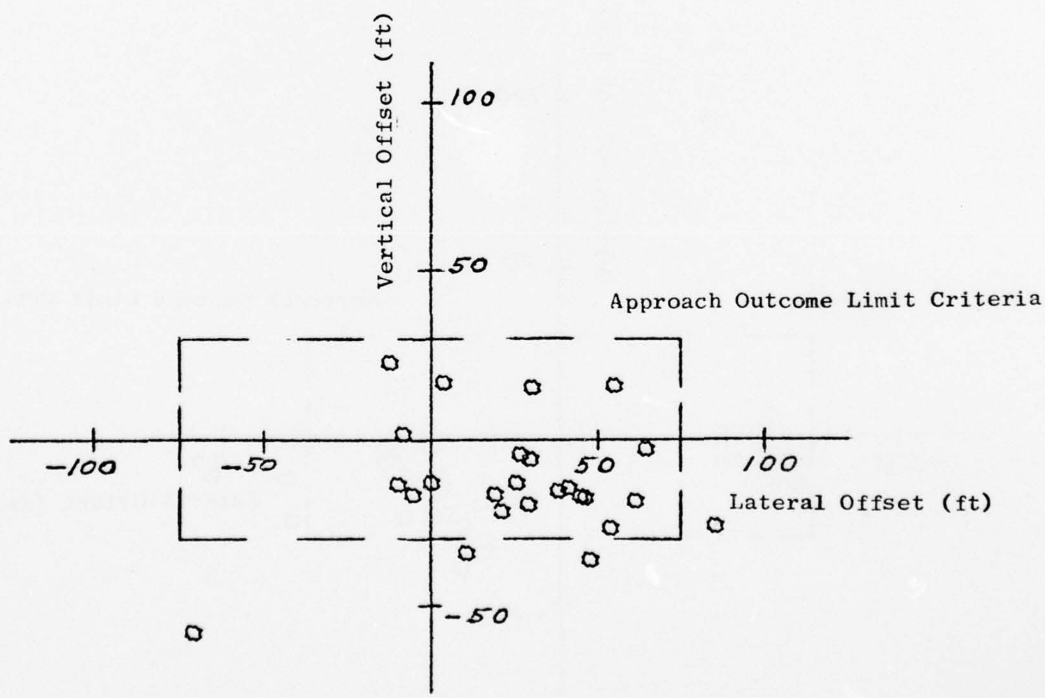
EXPT. #2 γ_{GM} WITH RAW DATA THUNDERSTORM



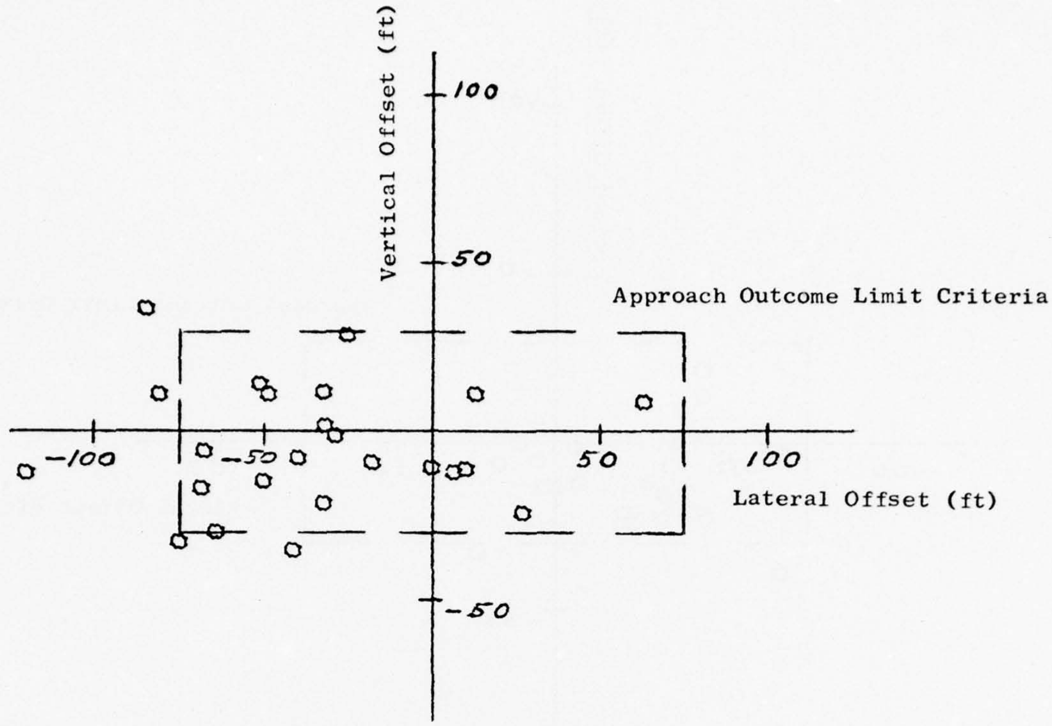
EXPT. #2 γ_H WITH RAW DATA THUNDERSTORM



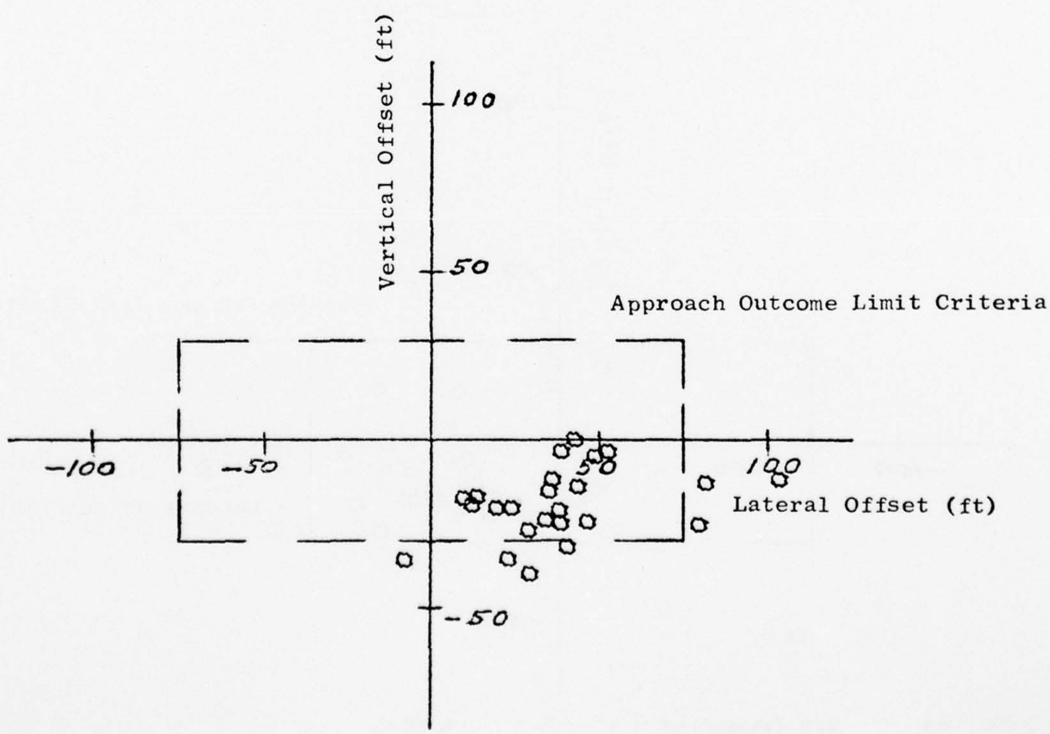
EXPT. #3 BASELINE FRONTAL



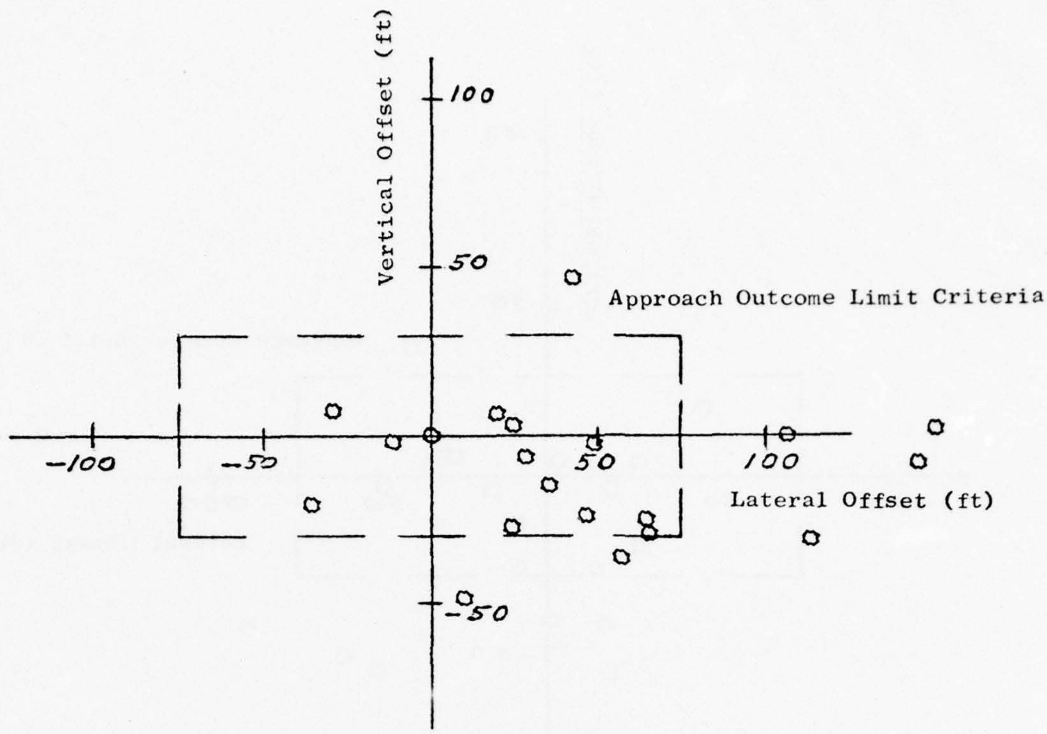
EXPT. #3 MFD (Modified Flt. Dir.) **FRONTAL**



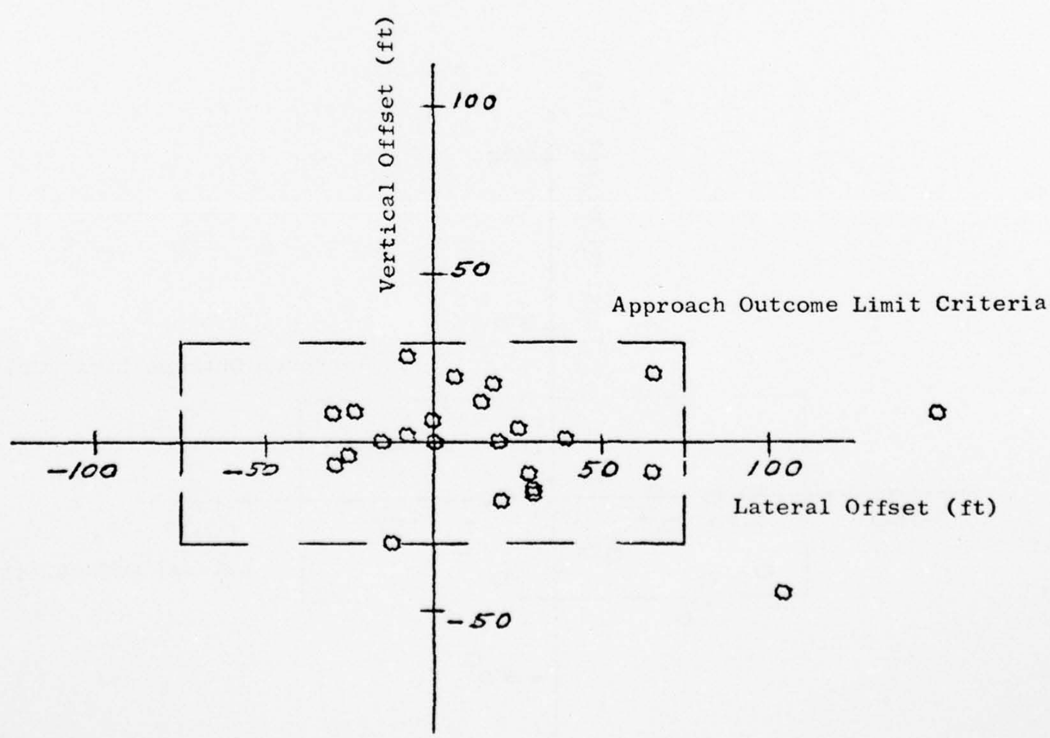
EXPT. #3 ΔW (Wind Differance) FRONTAL



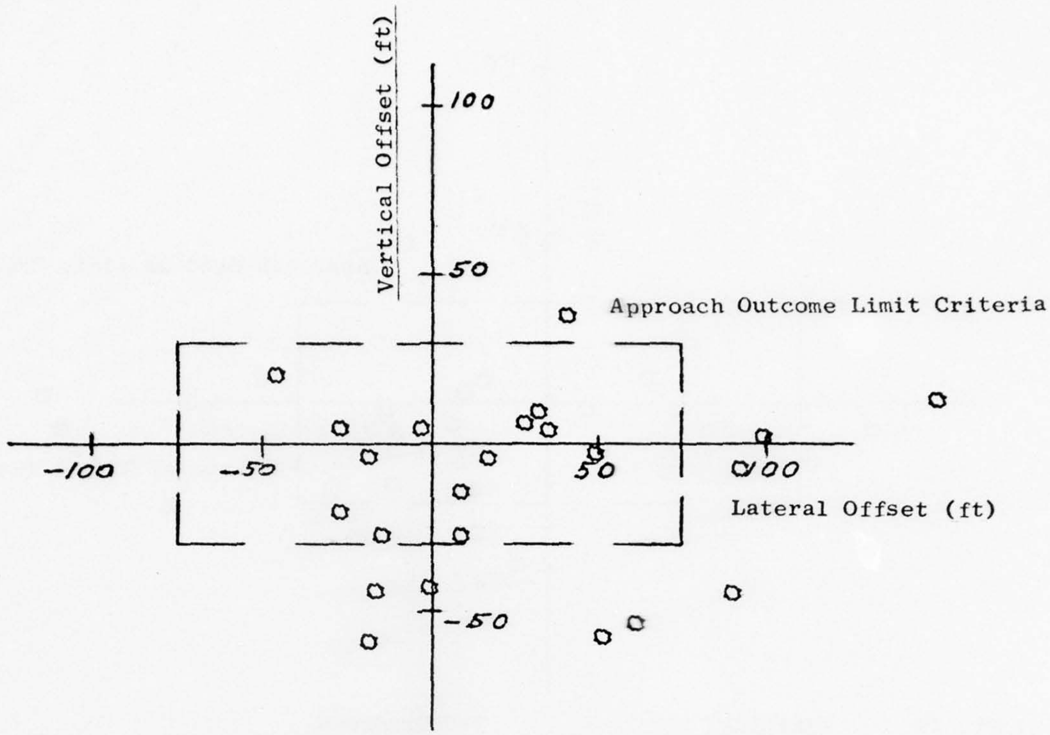
EXPT. #3 MFD/ΔW FRONTAL



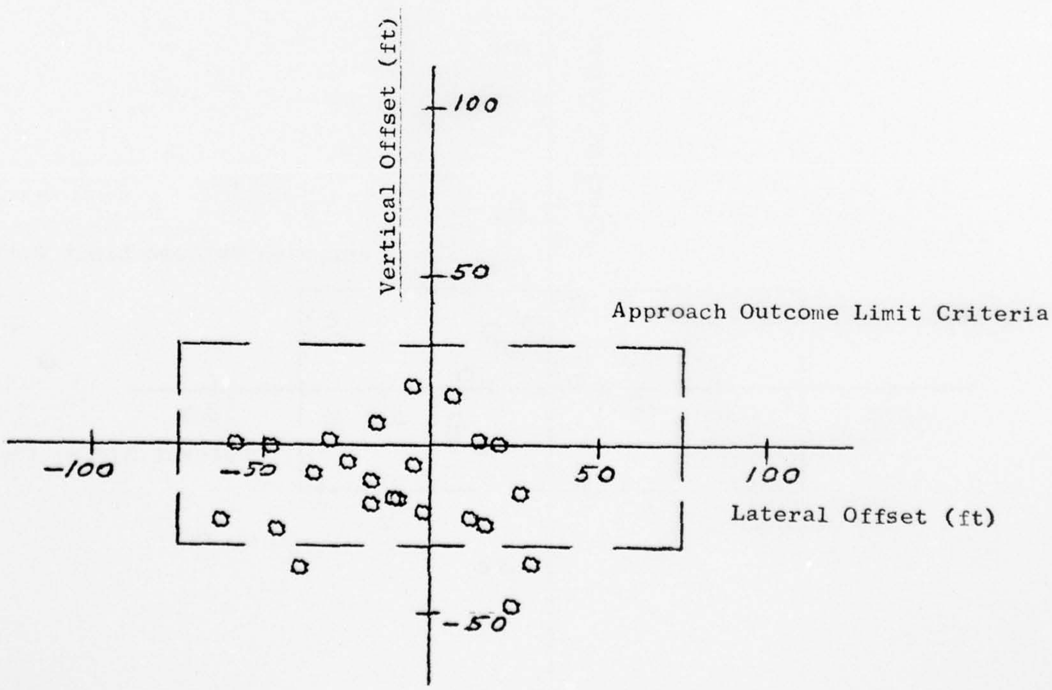
EXPT. #3 BASELINE THUNDERSTORM



EXPT. #3 MFD (Modified Flt. Dir.) THUNDERSTORM



EXPT. #3 ΔW (Wind Differance) THUNDERSTORM



EXPT. #3 MFD/ΔW THUNDERSTORM

REFERENCES

1. W. B. Gartner and A. C. McTee, "All-Weather Landing Systems, Engineering Services Support. Task 2--Head-Up Display. Piloted Flight Simulator Study of Low-Level Wind Shear, Phase 1," Interim Report (draft), Contract DOT FA75WA-3650, Stanford Research Institute, Menlo Park, Calif. (6 July 1976).

2. W. B. Gartner, "Task 2: Head-Up Displays--Plan for Accomplishing Phase 2," Contract DOT FA75WA-3650, Stanford Research Institute, Menlo Park, Calif. (5 August 1976).

3. SRI Request for Proposal No. ERU 4364-2, Stanford Research Institute, Menlo Park, Calif. (6 August 1976).

4. "Simulation Support Program, "Proposal 76D-445C, Douglas Aircraft Company, Long Beach, Calif. (24 August 1976).

5. G. H. Fichtl and D. W. Camp of NASA-Marshall Space Flight Center, Alabama, letter to Mr. Frank Melewicz, ARD-451, FAA (23 January 1976).

6. J. T. Fujita, "Spearhead Echo and Downburst near the Approach End of a John F. Kennedy Airport Runway, New York City," SMRP Research Paper 137, Department of Geophysical Sciences, The University of Chicago, Chicago, Illinois. (March 1976).

7. N. M. Barr, D. Gangass, and D. R. Schaeffer, "Wind Models for Flight Simulation and Certification of Landing and Approach Guidance and Control Systems," Report No. FAA-RD-74-206, Contract DOT-FA72WA-2934, Boeing Commercial Airplane Co., Seattle, Washington. (December 1974).

8. B. J. Winer, Statistical Principles in Experimental Design (McGraw-Hill Book Co., Inc., New York, N. Y., 1962).

9. L. V. Miller, "Report of Task 5, Phase 1, AWLS--Inertial Augmentation," Report, Collins Radio Group, Rockwell International, Cedar Rapids, Iowa. (August 10, 1976).